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DEVELOPMENT OF AN OPTIMAL SYSTEMS CRITERIA 
IN THE PERFORMANCE EVALUATION OF 
A CRAWFISH SORTING MACHINE

A Dissertation

Submitted to the Graduate Faculty of the 
Louisiana State University and 
Agricultural and Mechanical College 
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requirements for the degree of 
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in

The Interdepartmental Program in 
Engineering Science

by

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ABSTRACT

This study aimed to: 1) establish a set of optimally configured guidelines for performance testing of sorting crawfish sorting machines; 2) examine biophysical characteristics of crawfish and machine-related design parameters; and, 3) write computer programs covering the essential aspects of the crawfish sorting process.

Three crawfish sorting machines were tested in the Spring of 1994 and 1995: 1) cylindrical roller sorter machine, 2) diverging vane belt sorter machine, and 3) grid shaker sorter machine. Both the cylindrical roller sorter and the diverging vane belt sorter separated crawfish into four groups: peeler, medium, large and jumbo; the grid shaker sorter, however, separated crawfish into two groups: large and small.

Fortran 77 programs were written to facilitate analysis of data and to model the sorting process. In addition, prediction equations were developed for the following: total body length and carapace width, total body length and carapace depth, total body weight and carapace depth, total body weight and carapace width, angle of repose and total body weight both for PVC and aluminum surface.

The following variables were considered: sorter capacity, coefficient of separability, intensity of vibration, hopper opening height, roller speed, clearance between rollers or belts, and included angle between belts. Crawfish samples were randomly drawn from harvest catches during the season and
sorting runs performed at different combinations of the variables named. Treating capacity and coefficient of separability as response variables the data indicated that a curvilinear relationship existed among them.

The response variables attained maximum values within a definite range of the input variables. These ranges were as follows: 1) roller rpm: 40 to 46 rpm; 2) intensity of vibration: 10 to 20 Hz for both the cylindrical roller sorter and the diverging vane belt sorter and 15 to 20 Hz for the grid shaker sorter; 3) belt included angle: 80.12 to 110 °; 4) hopper opening height: 8 to 11 cm; and, 5) clearance: 11.98 mm (small end) to 26.42 mm (jumbo end) for the cylindrical roller sorter, 15.08 mm (small end) to 28.58 mm (jumbo end) for the diverging vane belt sorter, and 21.4 to 23.4 mm for the grid shaker sorter.

Performance ranking of the sorter machines followed the following order, highest to lowest: cylindrical roller sorter, diverging vane belt sorter and grid shaker sorter.
I. INTRODUCTION

Crawfish (*Procambarus clarkii*) has the potential to greatly affect the economy of Louisiana. On account of the weather and topography being ideal for crawfish production, Louisiana is strategically positioned to exert market dominance in the domestic as well as the international markets.

World food demands have recently shifted toward high protein, low-fat, and low cholesterol food which crawfish meat possesses. It is believed that in the next few years diet consciousness and physical fitness programs will boost the consumption of such food.

As a result of population pressures the issue of diversification of food sources is certain to be an important factor. Traditional food sources need to be supplemented by other sources so as not to overburden or strain current production systems. Also, tapping newer food reserves is less costlier mainly because monoculture presents environmental perils. Hence, aquaculture food products like crawfish meat provide society with a less expensive option. Moreover, there are opportunities in the processing or postharvest sector as a result of market shift from production orientation to consumer orientation. This trend is evident from the prevalent health-consciousness of consumers who seek fresher farm and aquaculture products while demanding fresher, fuller flavor.

At this point in time crawfish production in Louisiana is actively geared toward both the local market and overseas exports mainly to Europe.
By increasing cultured pond production and better management of wild sources in bayous and swamps Louisiana could very well be the leading producer of crawfish meat.

A vital component of this envisioned change in the crawfish industry is the processing sector. If crawfish meat is to be made available year-round in commercially acceptable standards it has to be processed satisfactorily. First and foremost is the sorting of newly harvested crawfish. When dealing with mass production quantities (world market standards) human sorting would be slow and expensive. A sorting machine that meets industry standards is an absolute necessity. Not only does it speed up handling and packaging thereby ensuring minimal product deterioration but it also helps establish grade differentials, an important consideration in the pricing mechanism. Peleg (1985) cited additional advantages of sorting as follows: (1) reduced dependence on seasonal manpower, (2) reduced cost of direct labor for sorting, and (3) objective and consistent sorting which is unaffected by worker fatigue.

Recently the Louisiana Voluntary Standard for Grading Crawfish (Roberts, 1994) was introduced in which the number of crawfish to a pound of live weight constituted the basis for classification: peelers -- 26 or more, medium -- 21 to 25, large -- 16 to 20, and jumbo -- 15 or less. This development is certain to spur interest in crawfish sorting machinery since sale and distribution of graded crawfish is expected in the next few years. Crawfish
sorters will be introduced and the crawfish producing community will be faced with decisions as to the relative merits of different designs.

There is currently a dearth of information about the technical aspects of crawfish sorting machines. In Louisiana a few large crawfish processors have successfully used the concept of oscillating parallel bars to separate out big crawfish for export. But there is no published literature to refer to as a yardstick for evaluating the performance of these systems.

Machine designers, extension engineers, local fabricators, and crawfish farmers would greatly benefit from research studies on crawfish sorters. In particular, they need to know suggestions and recommendations related to a) working principles applicable to sorting, b) performance indices such as sorter capacity and percentage of separability, c) the role of machine variables such as roller rpm, belt speed, hopper adjustments, clearances, vibration, and angular adjustments.

The object of this research study proposal is to break new ground in the area of aquacultural machinery development; in particular, it aims to combine theoretical and experimental work in order to resolve many important questions in the crawfish sorting operation.

Scientifically based improvements in the existing machinery and the development of new aquaculture machinery requires a broadening of the basis for its design. It is hoped that technology which can be generated from this would directly benefit the crawfish industry.
II. OBJECTIVES

A. General objective

To make a qualitative and quantitative study of the bio-physical factors influencing the performance of a crawfish sorter.

B. Specific objectives

1. To develop a computer simulation model of the crawfish machine-sorting operation;
2. To conduct model validation tests by means of controlled laboratory experiments;
3. To develop a set of criteria needed in the design of efficient crawfish sorting machines; and,
4. To introduce modifications in the existing crawfish sorting machines following the established set of criteria or standards.
III. REVIEW OF LITERATURE

A. Bodily dimensions of crawfish related to sorting and grading

Huner and Barr (1980) presented the following regression equations for weight and length of crawfish:

For males:

\[ \log W = -4.8850 + 3.2186 \log L \] (1)

For immature males:

\[ \log W = -4.8537 + 3.1552 \log L \] (2)

And for females:

\[ \log W = -4.9659 + 3.2196 \log L \] (3)

Where \( W \) = weight (grams); \( L \) = length (mm).

The carapace is roughly one-half of the total length of \( P. clarkii \). The mathematical relationship between the carapace length and the total length are as follows:
\[ TL = 2.6984 + 1.8581 \times CL \]  
(9)

\[ CL = -1.4522 + 0.5382 \times TL \]  
(10)

Where \( TL \), total length (mm); 
\( CL \), carapace length (mm).

Romaire et al. (1977) developed length-weight relations for red swamp crawfish and white river crawfish. For males, females, and immature males they reported the following equation \( (r^2 = 0.993) \)

\[ logW = -5.0537 + 3.2770 \times logL \]  
(11)

with the same nomenclature as before. Based on their sample frequency distribution the average for crawfish total body length fell on the 75 to 79 mm range; the minimum total body length occurred at around 50 to 54 mm range while the maximum total body length was at 135 to 139 mm range. They noted that the higher values of body weight for mature male crawfish was mainly due to its bulkier chelae. Lutz et al. (1987) used factor analysis to study the morphological variation in red swamp crawfish. They observed that carapace width and abdomen width can be viewed as positively correlated to the extent that both reflect overall body weight.
Brooks and Singh (1979) experimentally determined the coefficient of sliding friction, angle of orientation, and force required to eviscerate squid using pressurized water jet. Additionally, they presented linear regression equations characterizing squid bodily dimensions of which coefficients of determination were in the range 0.88 to 0.93. This study showed the basic methodology involved in the treatment of biophysical characteristics of aquacultural products.

Ling and Searcy (1991) investigated shrimp morphological features with the purpose of designing a machine-vision based automated shrimp \( (P.\ vannamei) \) deheader. Using spectral image processing they were able to accurately locate the point separating the carapace from the tail of the shrimp. Body configurations for shrimps were presented thus \( (R^2 = 0.6588) \):

\[
CLEN = 6.724 + 1.409 \ CWDTH
\]  

Where \( CLEN = \text{carapace length (mm)} \); \( CWDTH = \text{carapace width (mm)} \).

Speed requirements for the machine were at least 2 shrimps per second which exceeds the human rate of tail meat recovery.

B. Principles of sorting and grading machinery

Grading is the process of separating crop material into different classes which satisfy the requirements of industry and commerce; segregation is attained by making use of the product's differentiating characteristics.
The principal parameters governing the quality of grading and cleaning as follows: purity of material, biological quality of material, absolute or specific weight and uniformity of size.

Klenin et al. (1970) described the fundamental methods of grading according to the following properties of the material: geometric size of the particles, their aerodynamic properties, the shape and state of the surface, density and specific weight, electric conductivity and color.

Grochowicz (1980) summed up the probabilistic nature of sorting or separation as a process which can be achieved only when the following are observed:

(1) a significant difference in at least one differentiating characteristic (statistical testing methods),

(2) an external force causing the varied behaviour of the particle in a mixture,

(3) a separating surface (contact the element on which separation takes place).

**B.1 Grading by size.**

In grading by size sieves, rollers with fixed or diverging clearances and belt conveying surfaces as well as recessed cylindrical graders are used to separate materials according to different size groupings. An increase in effectiveness of grading may be achieved by employing a small amount of vibration whose main effect is to reposition particle orientation.
Motion at the delivery end of a flat separating surface is possible when the resultant of all forces acting on the particle exceeds the friction force (Klenin et al., 1985):

\[ \pm G \sin \alpha + P \cos(\varepsilon \pm \alpha) + R \cos(\gamma \pm \alpha) > F \]  \hspace{1cm} (13)

Where \( G \) = gravitational force; \( \alpha \) = angle of inclination; \( P \) = inertia force; \( \epsilon \) = inertia angle of rotation; \( R \) = airstream force; \( \gamma \) = airstream angle; \( F \) = friction force (= tan\( \theta \)).

Detailed development of equations of motion including sliding up and down, break of contact between particles, operating conditions of surfaces, and limiting velocity of particles were given. Methods were also developed for determining clearances between separating surfaces. This considered deviation from the mean value as predicted using the normal curve.

Loading of separating flat surfaces could be determined from the following equation (Klenin et al., 1985):

\[ q_s = q F_s \]  \hspace{1cm} (14)

Where \( q_s \) = amount of grading machine output; \( q \) = specific loading per area; \( F_s \) = area of separating surface.

Operating conditions can be specified for a material after experimental tests. This information describes unique points for kinematic factor, angle of inclination, and angle of rotation.
Airflow considerations (aiding motion by providing lift) influence the computation through the R-factor in particle motion. Methods have been described for determining size of air ducts, selection of blower and regulation of airflow systems.

Balascio et al. (1987) modelled the movement of grain particles under the action of gravity separation. They pointed out the impracticality of writing individual equations of motion for thousands of grain particles which would then require an unmanageable matrix of boundary conditions. In place of this they tried the Markov Probability Model, an approach which simplifies the problem because the Markov process can be thought of as being associated with particle positions alone. On testing this idea on soybeans they found the model to perform well.

**B.2 Grading by density and specific weight**

In grading materials according to density and specific weight size groupings are obtained by the use of airflow, floating the product in liquid suspensions, and the use of lever weighing mechanism.

The capacity of a belt separator to perform separation depends upon the motion of particles on the belt surface as defined below (Klenin et al., 1985):

\[
m g \frac{du}{dt} = G \sin \alpha - F_{\text{max}}
\]

(15)

Where \( m_g \) = particle mass; \( u \) = particle relative velocity;

\( t \) = time; \( G \) = gravity constant, \( \alpha \) = belt inclination angle;
\( F_{\text{max}} = \) maximum friction force.

The time \( t_1 \) for the particle to move a distance \( l \) is given by (metric units)

\[
t_1 \geq \sqrt{\frac{l \cos \theta}{4.9 \sin(\alpha - \theta)}}
\]

(16)

Where \( \theta = \) surface coef. of friction.

Feller et al. (1985) working on recessed cylindrical sorters used the location of the center of gravity in separating bad peanuts (single seeds, half-seed pods) from good peanuts. Here, the recesses in the inner wall of the rotating drum were designed so that good peanuts were ejected in a collection trough at higher angles while bad peanuts were ejected at lower angles. Data showed 80% rejection of bad peanuts with 1% loss of good peanuts.

**B.3 Grading by electrical properties**

In grading of material by electrical conductivity use is made of electrostatic fields and corona discharge fields in conjunction with the dielectric properties of the material as basis for separation. Materials with a high dielectric constant are directed to another trough, separate from those with low dielectric constants.

**B.4 Grading by color**

In grading by color the use of photoelectric effects are made the basis for sorting the materials into the desired size groupings. Depending upon the color of the agricultural material the current excited in the photoelement varies in
magnitude. Darker colored materials are charged positively while lighter materials, negatively. The lighter colored materials are directed to another receiver.

**B.5 Aquaculture sorting machinery**

A new prototype crawfish grader was invented, developed and tested by personnel of the Louisiana Agricultural Experiment Station (McClain, et al. 1993) which proved effective in sorting crawfish into three market categories. Departing from conventional designs this sorter separates crawfish while "in their natural environment"; that is, underwater, taking advantage of their natural behavioral response (crawfish instinctively swim to the bottom). Parallel bars which perform the separation process are immersed in a water tank. These bars are then lifted out of water by a hydraulic mechanism and the sorted crawfish discharge on an inclined receiving platform. Rated capacity of the prototype sorter was 706 to 1188 lb per hr of crawfish (two-man crew).

The New England Fisheries Development (Sackton, 1982) described the concepts tried in sorting squid as follows: divergent rollers, vibrating slots, and rotary sorter with adjustable opening vane. All these proved unsuccessful due to the compressibility of squids. However, work in Holland offered promise -- the use of counterweight buckets. This design was calibrated in 2 oz. (57 g) increments for grading squid. Test results demonstrated that this grader could sort squid in 2 oz. increments (57 g) with a 95% accuracy of ± 28 g (1 oz.). Also,
using this machine it was found that weight-length relationship indicated that 2 oz. increments related to ± 1 inch (25.4 mm) in mantle length. This means that a processor could use a weight grading machine and relate the weight increments to a buyer’s specification on mantle length with a large degree of reliability.

Many researchers reported on-site sorting in which undersized catch were allowed to escape through suitable openings in floating trap cages or boxes.

Moe (1991) described the use of grid sorters which can be used aboard lobster boats; it is nothing but a 3 x 5 ft. tray or box with the bottom composed of stainless steel bars placed 2 inches apart, or any other dimension required by law (selective fishing). Some laws mandate an escape gap of 2½ x 20 inches which must be built into the trap at the narrow end opposite the buoy line. Research with escape gaps like this have shown that 97 to 99% of undersized lobsters escape.

Wang and Williamson (1980) successfully used this floating type of grading unit for prawns, floating boxes made of accurately spaced rigid parallel bars. According to them the prawns are territorial by nature with the small prawns avoiding large prawns.

Lovshin and Phelps (1994) evaluated a German-designed mechanical grader for fingerling channel catfish. This machine sorts catfish according to length by means of a diverging belt, propelled by a 110-V, 0.25 kW electric
motor which rotated at 15 rpm. The belts face each other at an angle of 70° to form an open-bottomed, V-shaped trough 3 m. long. Compared to manual sorting (using parallel-bar grader boxes) the mechanical grader showed lower standard deviations for catfish length within four size groups (p>0.05). This mechanical grader was also equipped with a bioscanner or counter which was found to be accurate at the lower size ranges but tended to overcount longer catfish.

C. Optimal systems criteria in sorting and grading

The performance of a sorting machine is considered to be optimum when the following are met: machine run at operating conditions which maximize rated capacity, sorting process which minimizes product loss or contamination due to off-grades (strict separation based on one or more differentiating characteristic), and ergonomic design features which facilitate human control during the sorting process.

C.1 Problems in sorter optimal systems

There are many difficulties inherent in the development of optimal systems criteria in sorting or grading.

At the outset it is hard to quantify sorting output which depends a great deal on human visual judgment. Another point is that the response of machine-related variables cannot be predicted with mathematical certainty because of the complex and probabilistic nature of sorting operations (e.g. multi-layer particle movement in feed hoppers); Skoglund (1967) cited the need for special
considerations as a result of statistical variations. Then again a set of parameters always forms an interdependent system in which change in one could drastically affect the other variables. It is also a well-known fact that the dynamic behaviour of many commercial products varies over a wide range depending on a host of factors of which primary are moisture content, temperature, and relative humidity (and many of these have not yet been extensively studied). Also, raw material characteristics such as homogeneity and degree of contamination is another changeable item, varying from place to place and from season to season. Finally, many prior studies on sorting were done in isolation; the modern trend now is to look at the postharvest operations as an interlinked system, forming a positive feedback loop (Shewfelt and Prussia, 1993).

C.2 Proposed Optimal Systems

Peleg (1985) proposed to optimize sorting operations in accordance with the following factors: (1) variations in material input flow, (2) weighted sorting error, and (3) weighted sorting efficiency.

Firstly, he started with a relative value function $K$ for different grades $i$ as follows:

$$K_i = \text{relative value of different grades } i, \text{ usually } \sum K = 1 \quad (17)$$
He then defined sorting error $S_w$ as a summation of the ratio of differences between product inflow and outflow rates:

$$S_w = \Sigma \left( \frac{QF_i - P_{gi}G_i}{QP_i} \right)W_i$$

(18)

And weighted sorting efficiency as

$$E_w = \Sigma \left( \frac{P_iG_i}{QP_i} \right)W_i$$

(19)

Where

- $Q = \text{material input flow}$,
- $P_{gi} = \text{pure products fraction of grade i}$,
- $G_i = \text{product outflow, grade i}$,
- $W_i = \text{weighting function}$,
- $W_i = \frac{K_iP_i}{\Sigma K_iP_i}$.

Thus, combining the expressions for $S_w$ and $E_w$ he obtained mutually deterministic sorting quality indices which are shown below:

$$S_w + E_w = 1$$

(20)

It can be seen that sorting error $S_w$ is directly proportional to the material product outflow $Q$ while sorting efficiency $E_w$ is inversely related to it.
And weighted sorting efficiency as

\[ E_w = \Sigma \left( \frac{P_G i}{QP_i} \right) W_i \]  

Where
\begin{align*}
Q & = \text{material input flow}, \\
P_{gi} & = \text{pure products fraction of grade } i, \\
G_i & = \text{product outflow, grade } i, \\
W_i & = \text{weighting function,}
\end{align*}

\[ W_i = \frac{K_i P_i}{\sum K_i P_i} \]

Thus, combining the expressions for \( S_w \) and \( E_w \) he obtained mutually deterministic sorting quality indices which are shown below:

\[ S_w + E_w = 1 \]  

It can be seen that sorting error \( S_w \) is directly proportional to the material product outflow \( Q \) while sorting efficiency \( E_w \) is inversely related to it.

Pitts and Hyde (1986) set out to define criteria for ideal potato seed
pieces in terms of size, shape, and amount of cut surface and then to develop computer algorithms to optimize cutting patterns for a range of tuber sizes. The reason for this was that non-uniform stands in potato resulted from improperly cut potato seed pieces (affected seed viability). They were able to make positive recommendations but the highlight of their work was in their rational approach to optimizing production systems.

C.3 Capacity

Conformity between the load and rated capacity of a machine is achieved by selecting the optimum value of the width and the speed of the unit, considering a unit quantity for yield. These parameters may be expressed in metric units as (Klenin et al., 1985)

\[ q_{opt} = 0.01 \times B \times v \times Q \]

Where \( q_{opt} \) = optimum rated capacity; \( B \) = machine width; \( v \) = machine velocity; \( Q \) = yield quantity.

For a given rated capacity, the working width and speed of the machine are selected according to the working conditions and available power resources.

Portiek and Saedt (1974) developed an analytic and descriptive model for the potato sorting process (hand sorting on a roller conveyor). Their models worked for sorting on the basis of "good" or "bad" potatoes, i.e., only on two quality classes. Consistent with this system limitation they used the binomial probability distribution function to characterize sorting parameters.
They reported their equation for the analytic model as follows:

\[
\lim_{N \to \infty} \text{Prob} \left[ \frac{\Sigma (k_i - \Delta k_i)}{\Sigma (n_i - \Delta k_i)} \leq P \right] = 1
\] (22)

Where

\(N = \text{total sample size,}\)
\(k_i = \text{number of rejects before sorting,}\)
\(\Delta k = \text{number of rejects picked, one section,}\)
\(P = \text{maximum fraction of rejects after sorting.}\)

The interpretation is that for sufficiently large sample of sections it is "virtually certain" that the total fraction of rejects in these sections does not exceed the value \(P\) (the sorting capacity \(r\) must satisfy this requirement).

For the descriptive model the researchers proposed

\[
r \geq \beta_1 \frac{p-P}{1-P} \ln \beta_2 \log \left[\frac{(1-P)p}{(1-p)P}\right] \sqrt{\text{var}(k)}
\]

Where

\(r = \text{sorting capacity},\)
\(\beta_1, \beta_2 = \text{parameters det. experimentally,}\)
\(n = \text{number of objects per section,}\)
\(p = \text{fraction of rejects before sorting.}\)
C.4 Efficiency

Factors affecting the quality of operation may be assessed in terms of the quantity of material separated and the total quantity of material delivered to the grading or sorting machine. This could be monitored continuously by various types of measuring devices.

In the case of potato graders Klenin et al. op cit. used a measure of performance called grading coefficient \( \varepsilon' \) which may be expressed as follows:

\[
\varepsilon' = \frac{G}{G_S} \times 100\%
\]

Where

\( G = \) weight of the tubers of a particular size leaving a grade as per specifications,

\( G_S = \) total weight of material being graded.

They noted that compared to roller grading machines belt grading surfaces hardly damage the material and their grading efficiency depends little upon variations in the feed rate.

A theoretical criterion (Grochowicz, 1980) of the separability of a mixture \( \lambda \) according to a given characteristic is described by a two-parameter function:
\[ \lambda = \frac{\Delta_0 - \Delta}{\Delta_0} = 1 - \frac{\Delta}{\Delta_0} \]  \hspace{1cm} (25) \]

*Where* \( \Delta_0 \) = range of charac. values, two-component mix; \( \Delta \) = range of charac. values, both coincide.

The following cases are encountered:

Case I: \( \lambda = 0 \) Mixture is inseparable.
Case II: \( 0 < \lambda < 1 \) Mixture is separable with difficulty.
Case III: \( \lambda = 1 \) (\( \Delta \leq 0 \)) Mixture is easily separable.

Or, using a time-dependent degree of separation \( \eta \),

\[ \eta = 1 - \exp\left(\int_0^t P_s \, dt\right) \] \hspace{1cm} (26) \]

*Where* \( t \) = time of separation; \( P_s = f(t) \), intensity of separation.

For small loads and constant composition of the input mixture at the feed hopper

\[ P_s = \text{constant} = c \] \hspace{1cm} (27) \]

and the above equation reduces to

\[ \eta = 1 - \exp(-ct) \] \hspace{1cm} (28) \]

This means that separation is perfect at \( t \) approaching infinity or that the separation effect is random at short time intervals.
Further, Grochowicz introduced the concept of separating power $Z_r$ (amount of basic material in sorted set) and separating loss $Z$ (amount of basic material in rejects fraction).

Starting with 100% input set of raw material $M_w$

$$M_w = a_o + b_o$$  \hspace{1cm} (29)

Where $a_o = a_1 + a_2$; $b_o = b_1 + b_2$

in which the sorted set $P$ and the rejects set $Z$ are defined by

$$P = a_1 + b_1 ; Z = a_2 + b_2.$$  \hspace{1cm} (30)

Therefore, separation power $Z_r$ can be expressed as

$$Z_r = \frac{a_1}{a_1 + b_1}$$  \hspace{1cm} (31)

and correspondingly, separation loss $Z$

$$Z = \frac{a_2}{a_1 + a_2}$$  \hspace{1cm} (32)
The sorting process is optimal when $Z_r$ is maximum while $Z$ is minimum. The expressions above could also be set up as time integrals since the entire sorting process takes place over a definite time span.

Another measure of the course of separation process can be expressed in product form as follows

$$
e = \left( \frac{a_1}{a_1 + a_2} \right) \left( 1 - \frac{b_2}{b_1 + b_2} \right) \tag{33}$$

in which the first term in the right member of the equation describes the size of the yield of the basic material compared to the input quantity and the second -- the degree of removal of the contaminants.

The quality of the sorting process, is, however best reflected by the following equation

$$
\epsilon_1 = \frac{a_1}{a_2} - \frac{b_1}{a_0} \tag{34}
$$

or, alternatively,

$$
\epsilon_1 = \frac{b_2}{b_0} - \frac{a_2}{a_0} \tag{35}
$$
The value for $\varepsilon_1$ when separation is perfect is +1 while for a reverse process it is -1 (basic material passes through the outlet for contaminants).

C.5 Product classification

Klenin et al. proposed a method for determining the variation of the dimensions of classified produce. They called this method the use of variational series and variational curves which is essentially governed by the Gaussian probability distribution function. Here it is necessary to make individual measurements of 300 to 500 samples. The number of classes is in the range 5 to 10. The class intervals are assumed to be equal to the number of equations obtained from a division of the difference between the smallest and largest values of the measured quantity by the number of classes.

D. System modelling

D.1 Model

Ward (1985) offered a concise description of models and modelling as follows: A model is a set of mathematical relationships which represents the interaction of a system. The relationships are based on various assumptions whose degree of simplification conform with the objectives of the model.

Models can be static (viz. time is constant) or dynamic (viz. time is variable) -- the latter are commonly used in describing agricultural production systems. Agricultural systems model can either be deterministic (viz. makes definite predictions and ignores random elements) or stochastic (viz. takes the probability of an event into account).
It is important to realize, however, that models are only as good as the data and relationships on which they are based; and the model designer has control over these.

Thus, a model defines the interaction of a system. The system is a complex set of interrelated components operating within a given boundary. Systems generally have a hierarchical structure, comprising a number of subsystems. The extremities of a system are defined by its boundary which is the ultimate division between the system and its environment. Most systems are influenced by elements of their environment known as exogenous variables which can either be controllable or uncontrollable. The model designer can study the effects that changing one or more of the exogenous variables has on the elements of the system -- the latter known as endogenous variables.

In the development of a model it may be necessary to include a cybernetic (feedback) facility whereby the model output at one point in time can have a direct effect on the output of the system at a later stage.

The following are the fundamental steps in model development:

Step 1. Define system and construct system diagram
Step 2. Define system interactions
Step 3. Quantify the relationships of the system
Step 4. Construct computer flow chart
Step 5. Computer program development
Step 6. Validation of model
Smith (1977) presented essentially the same steps in engineering modelling and simulation. However, he emphasized that mathematical models for digital simulation which are based on both time-domain considerations and frequency-domain considerations are better than mathematical models based on either one alone. Moreover, he justified system simulation on the basis of the following: (1) the need to conduct a low-cost study or design of a system whose complex nature precludes a development in a laboratory experiment or as a scale model; (2) the need to verify that a system of mathematical modelling equations which are to be used in a control system are valid; and, (3) the need to forecast the response of a system to complex controls or policies as a means of evaluating the consequences of control or policy alternatives.

Hunt (1966) enumerated the tests for system models as follows: (1) compatibility with other systems interacting with it; (2) stability of operation despite wide fluctuations in the inputs to the system; and, (3) sensitivity to the important input parameters that control performance.

Dym (1994) underscored the overriding significance of mathematical or computer models in the engineering design process; criteria for design evaluation can be stated and applied either in terms of the representation, models or otherwise, used in the problem-solving phase of the design process or in terms of the formalisms used for the design and fabrication. Kardashevskii et al. (1985) pointed out the criterion function of a model as basically a means for verification of information regarding the original
machine prototype; this introduces the possibility of bringing more clarity into the information experimentally obtained.

**D.2 Similitude and dimensional analysis**

The theory of similarity (geometric, kinematic, kinetic) applies to process equations while dimensional analysis is applied to the determining equations (dimensional formulas which are invariant with respect to metric transformations).

Heatwole *et al.* (1982) described a systematic approach for determining all possible sets of dimensionless numbers with the aid of a computer program. The output from the computer program allows the investigator to review these sets without making exhaustive calculations and then to choose one which best fits his experimental capabilities. A requirement for this computer analysis is that there must be linear independence of the $\pi$-terms.

The problem is worked out analytically to determine the conditions necessary and sufficient for the group of $\pi$-terms to be a dimensionless quantity. Thus, the number of dimensionless groups is equal to the number of all the quantities ($m+r$) which are of importance for the process less the number of primary quantities. Dimensional analysis starts with Buckingham's $\pi$-Theorem as follows:
\[ \pi = x_1^{a_1} x_2^{a_2} \cdots x_m^{a_m} y_1^{\beta_1} y_2^{\beta_2} \cdots y_r^{\beta_r} \]

*Where*

\( x_i^{a_i} = \text{primary quantities } (i = 1, m) \),

\( y_j^{\beta_j} = \text{secondary quantities } (j = 1, r) \).

Several authors discussed the fundamental theory of similitude and dimensional analysis. Notable among these were Murphy (1950), Kline (1965), Gukhman and Cess (1965), Skoglund (1967) and David and Nole (1982).

**E. Crawfish sorting machines**

**E.1 Diverging vane belt crawfish sorter**

This is the largest of the three sorting machines. It consists of a parallel pair of inclined "V" linked vane-belt, 86 inches center-to-center distance, with a narrow entering clearance which diverges by fixed increments toward the other end. A crawfish is held by this belt until it drops to any of the five outlets depending on its size. Smaller crawfish are diverted near the entrance section. A perforated pipe runs through the upper section of the belt, providing water spray to facilitate sorting.

It runs off on two variable speed 0.1864 kw (¼ hp) Ac motors. Motor rpm is adjustable from 40 to 120. Figure 1 shows a perspective view of the vane belt sorter.
Using Reuleaux' (1963) uncontracted notation to describe its sorting mechanism we have the following for the drive system:

\[ C^-|...C_z^-,T_p^-,...\rightarrow T_p,-C_z^-|...C_z^-,C^-|...C_z^- \]

(37)

(i) (II) (III) (IV)

Toothed cylindrical gears (driven by electric motors) (I) are fixed to coincident vane-belts or prismatic tension-organs (II) which are concurrent and co-axial with each other (III); the pair of gears are fixed to a frame and have parallel axes (IV).
The pair of vane-belts carry crawfish material in a pseudo-fluid drive system at an oblique angle (diverging clearance) to each other (V); this link connects to link (II) in the drive system above.

**E.1.1 Mechanism of sorting**

Like the cylindrical roller sorter the diverging vane belt sorter conveyed the crawfish along a diverging clearance. The crawfish then dropped to a space in the clearance according to its size dimensions. An incline below the moving belt led directly to four compartments corresponding to peeler, medium, large, and jumbo.

Unlike the cylindrical roller sorter, motion of the crawfish in the diverging vane belt sorter could be mainly explained by contact friction between the moving belt and the crawfish. A small amount of component force, however, assisted the motion of crawfish along the belt as a result of the small depressions (Figure 2) or ridges between two linked portions of the vane belt.
Figure 2. Top view of the diverging vane belt sorter showing motor drive.

Crawfish fell in a random fashion in the sorting chamber between the V-section of the belts (Figure 3). As it hit the throat of the V-section its lower body parts dangled between the lower edges of the belts as in the cylindrical roller sorter. Since the flat surface of the belt tended to position the crawfish on its underside, carapace depth as opposed to carapace width in the cylindrical roller sorter appeared to be the controlling dimension. Another characteristic feature of the sorting process here is that compared to the cylindrical roller sorter crawfish were subjected less to rotational forces.
This is disadvantageous as it increases the probability of the crawfish holding on to a misorientation along the sorting distance, for example, the crawfish longitudinal axis directly normal to the line of motion.

E.1.2 Horsepower requirement

Horsepower requirement of the vane belt sorter was determined using the Conveyor Equipment Manufacturers Association equation;

\[ H_p = \frac{T_e V}{33000} \]  \hspace{1cm} (39)
where $T_e =$ effective tension, lb

$$Te = LK_x(K_x + W_b(K_y + 0.015)) + W_m(L_rK_y + H) + T_p + T_{am} + T_{ac}$$

$V =$ velocity of the belt, ft/min

$L = 7.5$ ft, length of conveyor to center of terminal pulleys

$K_t =$ temperature correction factor

$K_x = 0.00068 (W_b + W_m) + A_S / S_i$

$W_b = 1.75$, weight of belt, lb

$W_m = 1.75$, weight of material, lb

$A_S = 2.15$ lb, belt tension or force required to overcome frictional resistance and rotate idlers

$S_i = 3.75$ ft, troughing idler spacing

$K_y = 0.34$, factor used to calculate the combination of the resistance of the belt and the resistance of the load to flexure as the belt and the load move over the idlers $H = 0.0$, net change in elevation

$T_p = 50.00$ lb, tension resulting from resistance of belt to flexure around pulleys and the resistance of pulleys to rotation on their bearings, total for all pulleys

$T_{am} = 5.00$ lb, tension resulting from the force to accelerate the material continuously as it is fed onto the belt

$T_{ac} = 0.0$, total of the tensions from the conveyor accessories
Program MACHDES calculated the horsepower range corresponding to the test belt speed of 13.77 to 61.77822 ft/min which was 0.02456 to 0.11216, respectively.

E.1.3 Initial stress field

Moreover, it was of theoretical interest to determine the stress field across the V-section of the vane belt sorter for the following reasons: 1) accurate prediction of the load acting between belt sides, 2) it affects the phenomenon of failure due to repeated loadings. The following equation was included in program MACHDES wherein analysis paralleled the method recommended for belt conveyors in the transport of mineral rocks (McLean, 1985):

\[ \sigma_v = \rho g (h_o - z)/(n-1) + [\sigma_{v0} - \rho g (h_o - z_o)/(n-1)] [(h_o - z)/(h_o - z_o)]^n \] (40)

where \( \sigma_v \) = mean vertical stress across channel cross section in kPa; \( \rho \) = bulk density of solid, kg/m\(^3\); \( g \) = gravitational acceleration, 9.81 m/sec\(^2\); \( h_o \) = overall height of hopper, m; \( z \) = depth of hopper, m; \( n \) = stress field parameter; \( \sigma_{v0} = \sigma_v(z_o) \), kPa; \( z_o = z \) at \( \sigma_{v0} \), m.

Based on computer iterations by MACHDES the stress field parameter was found to be 382, reaching a maximum mean vertical stress of 2.15 kPa at a belt inclination or included angle of between 80° to 110° (values differed only at the fifth decimal place). At the given loading rate of crawfish and belt
dimensions the stress may be comparatively small but with larger systems this could be very useful.

**E.2 Cylindrical roller crawfish sorter**

Two pairs of 6%-inch cylindrical PVC rollers rotate upwards to sort crawfish as they move from a narrow clearance (near hopper) to a wider clearance at the other end. The rollers have machined helical grooves to increase frictional contact needed to direct crawfish from the narrow clearance to the wide end. Four rectangular holes are provided underneath each pair of cylindrical rollers. Thus, there is a total of eight outlets making possible four size classifications. It runs on a 12V DC-motor.

The feed hopper is moderately inclined to permit sliding motion of crawfish as it falls to the narrow section of the roller. Its drive mechanism is described by the following:

\[
\begin{align*}
  &T^*_2 \ldots T^*_z, R^* \ldots | | C^*_z C^- \ldots | | C^- R^*, \quad (I) \\
  &| | C^*_z C^- \ldots | | C^- R^*, \quad (II) \\
  &| | C^*_z C^- \ldots | | C^- R^*, \quad (III) \\
  &| | C^*_z C^- \ldots | | C^- R^*, \quad (IV) \\
  &| | S^- R^*, \quad (V) \\
  &\ldots | | Q, S^- R^*, \quad (VI) \\
  &\ldots | | Q, S^- R^*, \quad (VII)
\end{align*}
\]

Coincident roller chain (I) is attached to a sprocket (II) and thence to parallel drive axle (run by electric motors) which is fixed to a frame (III); the continuous drive reaches to the other sprocket (IV) causing opposite linear motion of the belt link as seen in a plane.
Link (III) in the drive system connects to (V) via a pseudo-fluid drive (crawfish between two rollers) in which the pair of rollers are positioned obliquely (diverging clearance) and rotate in an anti-parallel upward motion; these pair of rollers are helically grooved forming a negative spindle; a roller thus forms a solid of revolution as one link (VI), running back to the axle fixed on a frame (VII) which goes to (I) in the sprocket drive. This is shown further in Figure 4.

Figure 4. Pictorial view of the cylindrical roller sorter.
E.2.1 Mechanism of sorting

Separation of crawfish into different size groups was greatly influenced by its geometric orientation as it fell onto the upward rotating, helically grooved cylindrical rollers. This is shown in Figure 5. The crawfish particles tossed and turned till it rested on its upper midsection, tail downward between rollers with the chelae spread across the axis of the rollers. At this point the crawfish fell to the outlet which matched its dimension. Thus, carapace width appeared to be the principal dimension involved. This orientation took place in a kind of relative motion with other crawfish (Figure 6).

Figure 5. Medium crawfish passing through clearance of the cylindrical roller sorter.
E.2.2 Forces and roller diameter optimization

Program MACHDES was developed to perform computer iterations as regards the forces acting on a point in the helical path of the cylindrical roller sorter. A force balance needed to optimize the roller diameter was incorporated in program MACHDES, directed mainly toward the minimization of crushing forces acting on crawfish particles. The mathematical analysis and the ensuing machine computation covered the whole range of variation in crawfish sizes.

From Figure 7a, considering an upward rotating pair of rollers with a given diameter $r$, the forces acting on a crawfish particle of basic dimension $r_B$ are body weight $W$, normal resisting force $N$, and frictional force $F$. 
Figure 7a. Forces acting on a crawfish particle in a cylindrical roller.

\[ 2F \sin \theta + W = 2N \cos \theta \]  \hspace{1cm} (43)

\[ F = \mu N \]  \hspace{1cm} (44)

where: \( \mu \) = coefficient of friction between crawfish and rollers;

\( W \) = weight of crawfish particle; \( F \) = frictional force.

Hence,

\[ 2 F (\sin \theta - \cos \theta / \mu) + W = 0 \]  \hspace{1cm} (45)

Since \( W \) (weight of the crawfish) cannot be negative

\[ \cot \theta > \mu \]  \hspace{1cm} (46)

But from figure below
Figure 7b. Forces acting on a cylindrical roller.

\[ \cot \theta = \left[ \frac{(r + r_B)^2 - r^2}{r} \right]^{1/2} \] (47)

This gives

\[ \frac{r_B}{r(2 + r_B)} > \mu. \] (48)

This equation establishes the maximum value for the radii of the rollers.

Another limiting condition on the size of the rollers is established in the following way:

The horizontal force \(F_H\), applied on the crawfish by the rollers can be represented by the following equations:

\[ F_H = 2 (F \cos \theta + N \sin \theta) \] (49)
Thus using $F = \mu N$ we obtain

$$F_H = W (\mu \cos \theta + \sin \theta) / (\cos \theta - \mu \sin \theta)$$

(50)

Therefore, the second limitation on the size of the roller is

$$F_{H_{\text{max}}} > W (\mu \cos \theta + \sin \theta) / (\cos \theta - \mu \sin \theta).$$

(51)

Computer runs showed that horizontal force $F_H$ upon the crawfish particles ranged between positive (crushing force) and negative (lifting or turning force) values. Experimental values for friction coefficient $\mu$ (Section VA.9) were inputted into the program. Results validated the design correctness of the existing cylindrical roller sorter diameter.

**E.3 Grid-shaker crawfish sorter**

Ten 1-inch plastic tubes are bolted parallel to each other in a horizontal plane at a spacing of $\frac{3}{4}$ inch. Crawfish is loaded in a rectangular hopper measuring $5\frac{1}{2} \times 24 \times 38$ inch and falls through this parallel-spaced tubes. The tube frame rests on four coil springs at the corners which is agitated by a variable-speed, eccentric mounted 120 VAC motor, causing vibratory motion. Smaller crawfish drop immediately below the shaker bars while larger crawfish are thrown toward the other end. Four outlets for two sizes are provided in the machine (Figure 8).
Following Reuleaux' notation its sorting mechanism is described by

\[
\frac{P_4}{f} \ldots \frac{P_{10}}{f} \ldots \frac{C^*}{f}
\]  

(52)  

(I)    (II)

The shaker assembly consists of ten equally spaced coplanar and parallel tubes which are supported by four compression helical springs; these springs are arranged perpendicular to the parallel tubes at the corners (I); this fixed link holds an eccentric-drive electric motor at its underside, a cylindrical force-closure system (II) normal and oblique to the springs. Further detail is shown in Figure 9.
E.3.1 Mechanism of sorting

Sorting crawfish using the grid shaker sorter is similar to the sieving process in which particles smaller than the mesh size passed through while the bigger ones were retained on the shaker tray. The main difference was that in the grid shaker sorter trajectory of the crawfish particles was constrained across the slightly inclined parallel, equally-spaced tubes. Thus, size separation occurred in only one dimension, that is, along the longitudinal axis of the crawfish (Figure 10).

Figure 9. Tier arrangement of the hopper, shaker tray and collector outlet of the grid shaker sorter.
Figure 10. Crawfish in the grid shaker sorter.

Compared to the other two sorters in the study (cylindrical roller sorter and the diverging vane belt sorter) this type of sorter is the most sensitive to thickness of the sorting layer. With poor operator control of thickness separation efficiency would be sacrificed. The reason for this is it is easy for crawfish at the top layers to slip over to the large-size outlet without ever touching the parallel tubes.
IV. METHODOLOGY

A. Model development

Model development focused on the sorting and grading process itself, concentrating on machine-related factors and operator controls which optimize the entire operation.

A.1 Database on crawfish

Technical data and other system-related information was compiled in a database which constitute the constraints or specifications for model building. This is needed in the choice of an acceptable differentiating characteristic which ensures the best conditions for separation and enables the choice of optimal parameters for the sorting machines. Parameters which have not been reported thus far were determined by experimental methods.

From these sample data frequency distribution series for significant differentiating characteristics was be constructed. Statistical measures were computed and inferences made on the assumption of normality of the distribution curves.

Grochowicz (1980) recommended statistical analysis of differentiating characteristics in combination with an immediate follow-up sorting process pre-test:

1. choice of differentiating characteristic as distinguished by the largest difference;

2. accurate selection of operating dimensions and kinematic
2. accurate selection of operating dimensions and kinematic parameters of the separating element, particularly in overlaps;
3. preliminary determination of the extent of loss during the sorting process and, therefore, the nature of the separation process (choice between the highest purity and the smallest loss).

The following physical properties of crawfish were identified: geometry (length, width, thickness), bulk and specific weight static friction, angle of repose. Regression equations were done using the following software or computer languages: Fortran 77, LOTUS, and Matlab. More than 90% of the crawfish samples used during tests were pond-fresh, live crawfish. Some crawfish samples (less than 10%) were harvested late during the afternoon and were stored in coolers; these were used immediately during the morning of the following day. More than 90% of the crawfish were red. Late during the season more white crawfish were intermixed in the samples.

A.2 Test Plan

A.2.1 Cylindrical roller sorter. This sorter had 8 outlets from 2 pairs of rollers with 4 size groups (peeler, medium, large, and jumbo) for each pair. A total of 6 independent test runs were conducted at various combinations of the following variables: clearance between rollers, hopper opening height, intensity of vibration, and roller rpm. A total of 15 sample crawfish were drawn randomly from each outlet and measured for total body weight and total
720 measurements for all tests. Crawfish used during the tests were pond-fresh live crawfish at spring temperatures. No water flow was used for this test although the crawfish were sprayed with water before and after every test to maintain their freshness and vigor.

**A.2.2 Diverging vane belt sorter.** This sorter had 4 outlets (peeler, medium, large, and jumbo) although it is possible to change the number of outlets by moving the partitions between compartments. A total of 11 test runs were completed for this sorter machine, each time randomly drawing 15 crawfish samples per outlet, making a total of 660 measurements for all tests. The variables which were varied during the tests were the following: belt clearance, belt speed, belt included angle, hopper opening height, and intensity of vibration. A recirculating type of water flow was used during half of the tests, spraying crawfish with water in the hopper and in the belts by means of perforated PVC pipes.

**A.2.3 Grid shaker sorter.** In this sorter machine sorted crawfish fell into 2 size categories: small and large. A total of 10 independent test runs were conducted, taking 28 crawfish samples per outlet for a total of 560 measurements on total body weight and total body length. As in the cylindrical roller sorter no water flow was used during the tests. The variables which were varied during the tests were: clearance between parallel shaker bars and intensity of vibration.
A.3 Similitude and dimensional analysis

The first part of this analysis was done for no-load condition of the crawfish sorting machine to test stability, stress distribution, and strain configurations. The next part consisted of with-load or flow conditions in which power units were turned on and the sorting machine run with a continuous load of crawfish as in normal operations.

The method of dimensional analysis was employed since no previous work exists on this particular topic. How the variables are logically grouped were established. It is expected that inputs from dimensional analysis would increase the quality of equations arrived at.

Alongside the foregoing, mechanical analogues from other similarly related machines were used as reference systems; current designs of analogous machines for shrimp, squid, or even potatoes provided useful starting points. From here, the crawfish sorting operation were examined in the light of established process equations in the traditional analytic manner.

A.3.1 Expressions for volumetric capacity and torque

The method of dimensional analysis was employed to find expressions for volumetric capacity and torque for the diverging vane belt sorter and the cylindrical roller sorter. The logical steps followed in order to come up with the desired dimensional groups are presented in this section.

Programs DIMCRS (2 in a set) and DIMVBS (2 in a set) were developed to make it possible to cover the entire range of possible combinations of groups.
to make it possible to cover the entire range of possible combinations of groups. The aforesaid programs took a while to write because although SUN4/UNIX system gave acceptable processing times on-line print-out of results was a little cumbersome. The first set of computer program performed stepwise calculations leading to nonsingular matrices. In the case of the cylindrical roller sorter the program progressively eliminated from an initial combination of 495 to 165, down to 45 nonsingular matrices. For the vane belt sorter the program started with 252 combinations to 84 then down to 34 nonsingular matrices. The second set of programs set up these feasible nonsingular matrices for the determination of the exponents of dimensionless groups. Further details are found in the Appendix.

**A.4 Simulation equations**

Prediction equations were developed to empirically describe the crawfish sorting operation as it applies to the different types of machines in this study (Section IIC). System components were separately analyzed and subsequently integrated to form an overall mathematical description of the process. These equations were written in Fortran 77 as it is the most widely used simulation language in engineering research.

The model mathematically described the operation of the following crawfish sorters, available at the LSU BAE Aquaculture Engineering Laboratory: diverging vane-belt sorter, cylindrical roller sorter, and grid shaker sorter.
A.4.1 Prediction of particle position, velocity and acceleration in a cylindrical roller sorter

Movement of crawfish particles following the helical or screw grooves in the cylindrical roller was be modelled using screw path theory. This is briefly elucidated in this section. Details of this are found in the Appendix.

A component in program MACHDES simulated displacement, angular velocity and acceleration, as well as linear velocity and acceleration of crawfish particles. An underlying assumption is only single particle motion takes place whereas the actual situation is a mass of live crawfish clumped together in groups of 3 or even as was observed during the tests in groups of 5 or 6.

The basic idea here is that correction factors can be introduced into the idealized case of single particle motion as provided for by screw theory.

B. Model output

The end-result of modelling is a set of values which will be useful to industries, designers, and biological engineering researchers. In this study it was proposed to come up with optimum specifications for the following variables: rate of loading, belt speed, taper clearance, water assisted flow rate, frequency of vibration, capacity, efficiency, power use, input product flow interruption, and grade classification.

Emphasis is put on the fact that although efficiency or capacity can be maximized the trade-off associated with it may be unacceptable. Therefore, at best, we can only settle for an optimum or acceptable value or range of values.
were grouped according to the following modules:

**B.1 Statistical/probabilistic component**

**Input:**
- a) body length of crawfish, mm
- b) A-data (body length, mm) from 4 sorter outlets
- c) size range for crawfish voluntary grade standard
- d) size range for existing crawfish sorting machines

**Output:**
- a) variational series analysis using size ranges following

\[ R = X_{\text{max}} - X_{\text{min}} \leq i \cdot h \]

Where
- \( R \) = range of random variate \( x \) (mm),
- \( X_{\text{max}} \) = maximum value of \( x \) (mm),
- \( X_{\text{min}} \) = minimum value of \( x \) (mm),
- \( i \) = number of class intervals \((i \leq 5)\),
- \( h \) = differences of intervals (mm).

b) frequency distribution of body weight
c) distribution curves showing overlaps; test significance of differentiating characteristics using or the \( \chi^2 \)-test
d) 2-d or 3-d plots of differentiating characteristics

\[ \sigma_x = \frac{(\mu_1 - \mu_2)}{\sqrt{\sigma_1^2 + \sigma_2^2}} \leq 3 \]

Where
- \( \sigma_x \) = standard deviation of difference for two size groups (mm),
- \( \mu_1, \mu_2 \) = means of two size groups (mm),
- \( \sigma_1^2, \sigma_2^2 \) = variances of two size groups (mm²).
B.2 Vibration component (for shaker-tray sorter and possible modification for existing machines)

Input: a) spring constant b) tray and tube dimensions
c) tray and tube masses d) damping constant due to load
e) motor rpm and frequency f) sorting efficiency and loss
g) depth of hopper load

Output: curves depicting system response to changes in input variables especially in relation to: a) sorting efficiency $E_w$ b) sorting error $S_w$ c) effect of depth of hopper load

B.3 Kinematic-machine component

Input: Vane-belt sorter a) vane-belt angle of inclination b) vane-belt speed (or motor rpm) c) vane-belt width d) loading rate of crawfish e) end-to-end clearance f) c-c distance between outlets Roller-sortera) roller rpm b) end-to-end clearance c) roller diameter d) helix angle of threads e) c-c distance between outlets f) loading rate g) hopper geometry

Shaker sorter a) motor rpm b) frequency of vibration c) amplitude of vibration d) damping coef. of hopper load e) distance between tubes f) tube diameter g) spring constant h) loading rate i) hopper geometry j) angle of inclination of hopper tray

Output: a) velocity curves b) acceleration curves c) power curves d) vibration response curves e) other system-related variables (links to optimal systems)
B.4 Peleg’s optimal system component (in-plant conditions)

**Input:**
- a) levels of $K_r$-function (relative value of the sorter grades)
- b) levels of material input $Q$
- c) levels of material output flow rate $G$ for all three sorters
- d) other input data (links to kinematic factors)

**Output:**
- a) response curves in terms of weighted sorting efficiency $E_w$ and sorting error $S_w$
- b) specification of optimal system

B.5 Grochowicz criteria component (in-plant conditions)

**Input:**
- a) data on separability $\lambda$ from all three sorters
- b) data on separation power $Z$ and separation loss $Z_r$
- c) data on sorting quality from all three sorters
- d) data on small load degree of separation
- e) other input data (links to kinematic factors)

**Output:**
- a) response curves for various criteria indicated above
- b) specification of optimal system

C. Model validation

The optimum values predicted by the computer simulation model were tested against actual experimental values. From here, a feedback loop process checked laboratory results. These tests were supplemented by field tests as stated earlier (section IVA).
C.1 Instrumentation

Time measurements were made using stopwatches and bodily dimensions of crawfish were determined using hand-held direct vernier calipers. For weight measurements corresponding to 4 size classifications of crawfish samples appropriate weighing scales were used. For making frequency counts of sample crawfish falling within a specific size configuration hand-held mechanical counters were used.

C.2 Machine calibration

C.2.1 Cylindrical roller sorter

To obtain the required roller rpm a variable voltage regulator was hooked to a 12V AC-DC converter. The AC voltage setting required to give the desired rpm was determined in conjunction with a hand-held mechanical counter and stopwatch. This is shown in Figure11. From these readings it was possible to accurately set the roller rpm during the tests.

The rate of discharge of fresh crawfish samples from the hopper depended on the opening height of the vertical sliding gate as well as the frequency of vibration of the motor underneath it.

It was observed that a crawfish, on the average, begins to slide down an aluminum surface at an angle of inclination of 24.2°. However, a mass of crawfish takes a steeper angle to begin to move down. Thus, the hopper tilt was correspondingly adjusted to 9.48° to allow for the role of vibration in accelerating the crawfish down the incline.
Since crawfish is not smooth-flowing unlike most granular materials it was difficult to adjust the sliding gate; however, a noticeable change in flow was observed when the sliding gate was varied by increments of one-third of the height of the hopper opening. Total height of the hopper sliding gate was 23.02 cm.

A component of Fortran program BIOPHYS was developed to determine hopper dimensions for no arching or bridging at the outlet, following the method of Mohsenin (1986). This program considered normal and tangential stresses exerted by the crawfish on the hopper walls. Performing a computer iteration for stress plane in the range 0 to 45° BIOPHYS predicted a hopper
opening width of 2.88 inches at an internal friction angle of 17.32° (hopper initial tilt angle added to this value). These figures were found to be slightly on the conservative side. They were made a reference values in making hopper height and inclination adjustments with perfectly satisfactory results.

C.2.2 Grid shaker sorter

The grid shaker sorter required no initial calibration except verification of the full operational range of the following variables:

1. Maximum load capacity of the aluminum hopper

This was found to be in the range of 15 to 22.5 lb of crawfish per batch load or about half of a normal harvest sack of crawfish. Loading of crawfish material beyond this range caused uneven sorting due to pile-ups at the central portion of the vibrating shaker tray which was made of parallel PVC tubes. The pile-up rate could be reduced by vigorous hand spreading but this required one more person to do the job.

2. Control switch for intensity of vibration

This was specifically a speed control for the rotating AC motor mounted eccentrically to its shaft housing. Based on a visual observation of the motion imparted upon the crawfish samples the speed control appeared to deliver a progressive, linear type of increase in rotational speed. It was thus found to be quite acceptable for testing. Number settings for the vibrator motor ranged from 0 to 10 which covered the frequency range of 0 to 20 cycles per second, or an increment of 1.67 per shift in number setting.
C.2.3 Diverging vane-belt sorter

Like the cylindrical roller sorter the diverging vane-belt sorter was motor driven. To achieve the required linear speed of the belt the speed control had to be adjusted correspondingly. The pair of AC motor speed range went from 0 to 100% full scale. Calibration tests were run to check speed adjustments for the range of speeds expected during sorting. Using a stopwatch and marking the linked acetal plastic belt the speed of travel was determined. Figure 12 shows the calibration curve.

\[ Y = 2.5923X - 14.1046; R^2 = 0.9924; n = 10. \]

Figure 12. Calibration curve for the diverging vane belt sorter
D. Modifications in existing machinery

Modifications or improvements were done on the existing crawfish sorting machinery at the LSU Department of Biological and Agricultural Engineering Aquaculture Laboratory. This was mainly pertaining to the hopper flow regulation device as well as provisions for water assist systems.

E. Test results

Test results including those of model development were stored in computer disks for reference retrieval by interested users. This could be material for patent application by the department.

F. Criteria and standards

A draft proposal on the performance criteria specific to crawfish sorting machinery was prepared following the ASAE Standards format and content. This will provide a common basis for testing, describing, or informing regarding (1) test conditions and procedures, (2) grading efficiency test, (3) calculation and formulas, and (4) method of reporting.
V. RESULTS AND DISCUSSION

A. Physical characteristics of crawfish

A.1 Sample distribution

A total of 552 sample crawfish were randomly drawn from freshly harvested sacks at Ben Hur Farms in February 1994 and 1995. Appendix B.1 shows the sample data on crawfish body weight. A frequency distribution plot of its weight (Figure 13) showed a bimodal curve with peaks at approximately 11.6 to 21.5 g and 34.6 g, respectively. Sample mean and standard deviation were 23.11 and 10.22, respectively. The percentage coefficient of variation was 44.02%.

![Figure 13. Frequency distribution of crawfish body weight.](image-url)
With reference to the voluntary standard for grade classification of crawfish the data in this study was approximately equally distributed into quartiles; that is, with \( x \) as weight in grams

\[
p(x \geq 30.23) = p(22.68 \leq x \leq 28.34) = p(18.14 \leq x \leq 21.6) = p(x \leq 17.44) = \frac{1}{4} \quad (55)
\]

Probability-wise an individual crawfish had the same likelihood of being picked to represent any of the four size groups (jumbo, large, medium, and peeler).

Table 1, Table 2, and Table 3 show the total weight and total number of counts of the samples used in the study for all three types of sorters.

Table 1. Weight (g) and count (in parenthesis) of crawfish samples collected from outlets of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Left pair of rollers</th>
<th>Right pair of rollers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peeler</td>
<td>Medium</td>
</tr>
<tr>
<td>1</td>
<td>106.4</td>
<td>523.1</td>
</tr>
<tr>
<td></td>
<td>(8)</td>
<td>(30)</td>
</tr>
<tr>
<td>2</td>
<td>156.3</td>
<td>1131.6</td>
</tr>
<tr>
<td></td>
<td>(12)</td>
<td>(68)</td>
</tr>
</tbody>
</table>

(table con’d.)
### Table 2. Weight (g) and count (in parenthesis) of crawfish samples in the grid shaker sorter.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Size classification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>1</td>
<td>6610 (854)</td>
<td>854 (28)</td>
</tr>
<tr>
<td>2</td>
<td>5940 (438)</td>
<td>802 (44)</td>
</tr>
<tr>
<td>3</td>
<td>8016 (569)</td>
<td>711 (39)</td>
</tr>
<tr>
<td>4</td>
<td>8690 (665)</td>
<td>612 (31)</td>
</tr>
</tbody>
</table>

Note: Percentage distribution of crawfish samples by weight (peeler, medium, large, jumbo) is as follows: 2.241, 16.886, 37.838, 43.035.

(table con’d.)
Table 3. Weight (g) and count (in parenthesis) of crawfish samples in the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Peeler</th>
<th>Medium</th>
<th>Large</th>
<th>Jumbo</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3904.5 (216)</td>
<td>2492.6 (117)</td>
<td>2290.5 (84)</td>
<td>3145.4 (79)</td>
</tr>
<tr>
<td>5</td>
<td>908 (61)</td>
<td>2356 (142)</td>
<td>4922 (258)</td>
<td>9656 (346)</td>
</tr>
<tr>
<td>6</td>
<td>409 (26)</td>
<td>1221 (74)</td>
<td>3014 (169)</td>
<td>6183 (281)</td>
</tr>
<tr>
<td>7</td>
<td>205 (16)</td>
<td>243 (16)</td>
<td>944 (60)</td>
<td>9120 (462)</td>
</tr>
<tr>
<td>8</td>
<td>1300 (96)</td>
<td>2527 (174)</td>
<td>7765 (448)</td>
<td>9016 (317)</td>
</tr>
<tr>
<td>9</td>
<td>3169 (197)</td>
<td>3084 (171)</td>
<td>4466 (237)</td>
<td>7133 (266)</td>
</tr>
<tr>
<td>10</td>
<td>436 (30)</td>
<td>778.5 (47)</td>
<td>17 (1)</td>
<td>3651.5 (163)</td>
</tr>
<tr>
<td>11</td>
<td>4109 (290)</td>
<td>5022 (338)</td>
<td>3896 (226)</td>
<td>2972 (141)</td>
</tr>
<tr>
<td>12</td>
<td>1505 (100)</td>
<td>2171 (134)</td>
<td>3441 (164)</td>
<td>9358 (326)</td>
</tr>
<tr>
<td>13</td>
<td>4908 (362)</td>
<td>4621 (302)</td>
<td>3368 (198)</td>
<td>3270 (135)</td>
</tr>
<tr>
<td>14</td>
<td>2402 (215)</td>
<td>3655 (286)</td>
<td>5638 (357)</td>
<td>5486 (307)</td>
</tr>
</tbody>
</table>

G. TOTAL: 88268 (6352)

(table con’d.)
A.2 Body weight and total body length

The samples were measured for body weight (g) and fitted initially on various forms of regression lines. Romaire’s equation (1977) was found to give the best fit, obtaining a coefficient of determination greater than 0.90.

This result promises to simplify future researches on crawfish because linear measurement of crawfish body length using a scaled perpendicular board takes more time compared to taking weight measurements. In the light of sorting studies this means that live crawfish can be kept fresh longer for new tests.

A.3 Body weight and carapace width

A total of 28 observations were taken to examine the regression between total body weight and carapace width. A hand-held direct reading Vernier caliper was used to measure carapace width. Figure 14 shows a satisfactory fit using a linear function.
\[ Y = 1.556648 + 0.021462X; \quad r^2 = 0.907802; \quad n = 48. \]

Figure 14. Prediction curve for body weight vs. carapace width.

**A.4 Body weight and carapace depth**

As previously, 28 crawfish samples were measured for the variable named. Figure 15 shows a satisfactory fit for the data using the linear function as the regression model.

**A.5 Total body length and carapace width**

Again, 28 crawfish samples were randomly drawn from a harvest lot. Total body length was taken using a scaled perpendicular board and carapace width using a direct reading Vernier caliper. Figure 16 shows the corresponding fitted regression line.
Figure 15. Prediction curve for body weight vs. carapace depth.

Figure 16. Prediction curve for body length vs. carapace width.
A.6 Total body length and carapace depth

The procedure followed here was similar to A.3, A.4, and A.5 above. A linear regression equation best fitted the given set of data. This is shown in Figure 17.

For 3, 4, 5, and 6 the following remarks apply:

a) Body weight was a better predictor ($r^2 = 0.901051$) for carapace width (CW) than it was for carapace depth (CD) ($r^2 = 0.818818$).

b) Total body length was a better predictor ($r^2 = 0.826472$) for carapace depth.

\[ Y = -0.16983 + 0.02960X; r^2 = 0.93897; n = 48 \]

Figure 17. Prediction curve for body length vs. carapace depth.
depth than it was for carapace width ($r^2 = 0.772039$).

c) Body weight was a better predictor than total body length for carapace width or depth (average $r^2$ of 0.85993 vs 0.79926, respectively).

d) Using the prediction equation from (a) above ($CD = 0.027386 \times \text{Body Wt.} + 1.43911$) as basis for clearance adjustments and referring to the Louisiana Voluntary Sorting Standard the clearances for sorting in inches would be

- **Peeler** — 0.75839 or less
- **Medium** — 0.75840 to 0.80529
- **Large** — 0.80530 to 0.88227
- **Jumbo** — 0.88228 to 0.95915 or greater

**A.7 Crawfish bulk density**

Sample live crawfish from different pond locations at Ben Hur were hand-mixed in container tubs. These were then loaded in box containers with the following dimensions: $5 \frac{3}{16} \times 10 \frac{3}{8} \times 12$ inches. The bulk density of freely moving crawfish without compaction was found to be 22.06 lb per ft$^3$.

**A.8 Crawfish particle density**

Individual crawfish density was determined using the volumetric displacement method. Using a large graduated cylinder filled with water crawfish samples with pre-determined weights were immersed and the change in volume recorded. Figure 18 shows the close correlation between crawfish body weight and volume of water displaced.
A.9 Angle of repose

Angle of repose was estimated by holding a live crawfish flat on the surface of the experimental sliding board. The sliding board was slowly lifted on an end and the corresponding angle recorded by reading the protractor close beside the sliding board. Reading was taken as soon as the crawfish began to move.

This took more than five trials per sample because crawfish on its own rapidly crawled out of the board independent of the motion of the sliding board. It was soon found that crawfish can be held partially immobile by pushing it flat on its underside and stroking its carapace for a few seconds.
Tests were conducted for two sliding board materials: PVC and aluminum. The prototype sorting machines in this study used these materials as contacting surface for crawfish.

A.9.1 PVC surface

Figure 19 is the plot of the linear regression line. It shows a general decrease in angle of inclination with sample crawfish body weight. Additional remarks may be made about the sliding phenomenon of live crawfish as it relates to PVC materials:

1) At 10° the crawfish is in static equilibrium, no sliding occurs.
2) At 11° fully wet crawfish just barely slides down the inclined.
3) At 18.5° crawfish slides very slowly on wet and new PVC board.
4) At 20° crawfish on its side with longitudinal axis normal to incline begins to slide.
5) At 20.1° refrigerated (immobile) crawfish begins to slide
6) At 25° crawfish on its side or back slides freely.
7) At 28° crawfish positioned head down with longitudinal axis parallel to incline, fully wet, with tail spread on surface begins to slide.

A.9.2 Aluminum surface

Figure 20 shows the regression line between crawfish body weight and the angle of inclination for an aluminum surface. The same type of equation as for PVC surface holds.
Y = 34.90822 - 0.28707 X \ (r^2 = 0.741071, n = 20).

Figure 19. Prediction curve of angle of repose of crawfish on PVC.

Y = 30.18398 - 0.27558 X \ (r^2 = 0.683635, n = 23).

Figure 20. Prediction curve of angle of repose of crawfish on aluminum.
Additionally, the following observations were made:

1) Between 21° and 24° crawfish began to slide at a position where it was lying on its back, head portion up or down the incline.

2) Between 23° and 25.5° crawfish began to slide down while lying on its underside with antennae and tails spread over surface.

3) Peeler size crawfish required between 27° and 34° in order to begin moving down the inclined surface and took higher values when it was positioned on its underside, head up, with the antennae and tails spread out.

For both tests crawfish samples were dipped in water to clear away crawfish excretions and closely simulate live sorting. The inclined boards were periodically washed with water to prevent build up of mucilage which tended to increase recorded angles.

**A.10 Computer program CFSTAT**

Program CFSTAT (Appendix A) was developed to compute the regression of crawfish body weight (g) with respect to body length (mm) based on Romaire's equation; also calculates sample statistics (sd, mean, range, intervals, frequency distribution) for actual sorter grades and for Louisiana Voluntary Standards.

**B. Sorting Capacity**

The quantity of crawfish per unit time collected from the outlets of the three sorting machines, primarily as a function of linear speed or intensity of
vibration was modelled using a cubic polynomial equation. Matlab software was employed to calculate the parameters or coefficients of the third-order polynomial. The goodness of fit was quite satisfactory with low values for residuals.

In descending order of magnitude of capacity the following was the results of the tests: grid shaker sorter, cylindrical roller sorter, vane belt sorter. The capacities, however, did not differ from each other by more than 17%.

**B.1 Cylindrical roller sorter**

Figure 21 shows the plot of the regression equation for the capacity of the cylindrical roller sorter as a function of roller rpm. It shows a curve whose slope noticeably increases above 35 rpm and pass through a levelling-off region beyond 42 rpm.

The aforementioned curve (capacity vs. roller rpm) agrees with the results from dimensional analysis (Appendix) where volumetric capacity was found to be directly proportional to revolutions per minute N.

Table 4 and Table 5 show the variation in capacity at fixed levels of rpm, hopper opening, clearance between rollers, and intensity of vibration. Drawing points from the table and treating the general functional relationship as a surface having the form

\[ f(c,v,h,\text{rpm}) = 0 \]  

(56)
where \( c \) is capacity in kg/min, \( v \) is vibration scale setting, \( h \) is hopper opening in inches, and \( \text{rpm} \) is roller rotational speed, we obtain expressions for the approximate rates of change as follows:

\[
\text{Pred. eqn.:} Y = -0.0020X^3 + 0.2173X^2 - 7.2856X + 77.932
\]

Figure 21. Prediction curve for cylindrical roller sorter capacity.
\[
\frac{\partial c}{\partial v} \bigg|_{h=\text{const.}} = \frac{(4.03726 - 1.97997)/(6 - 4.5)}{6 - 4.5} = 1.37153 \text{ kg/min per scale upward shift in vibrator motor speed setting.}
\]

\[
\frac{\partial c}{\partial h} \bigg|_{v=\text{const.}} = \frac{(4.36999 - 4.03726)/(9 - 3)}{9 - 3} = 0.05545 \text{ kg/min per in. increase in hopper opening.}
\]

Both quantities are positive describing a general pattern of increase in capacity with either hopper opening or intensity of vibration. The data, however, points to a levelling off part of the curve; that is, capacity reaching a maximum and then declines with a further increases in hopper opening height or intensity of vibration.

Table 4. Variation in capacity (kg/min) with roller rpm, hopper opening, and intensity of vibration for cylindrical roller sorter.

<table>
<thead>
<tr>
<th>Roller rpm</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hopper open. = 3 in Vib.=4.5</td>
</tr>
<tr>
<td>20</td>
<td>1.97997</td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td></td>
</tr>
<tr>
<td>40.5</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.97997</td>
</tr>
<tr>
<td>Mean</td>
<td>1.97997</td>
</tr>
</tbody>
</table>
Table 5. Variation in capacity with hopper opening, clearance setting and intensity of vibration of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th>Hopper opening, h in</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vib. = 4.5 Clear=.445,.499 (H);1.082,.999(D)</td>
<td>1.97997</td>
</tr>
<tr>
<td>Vib. = 5 Clear=.445,.499 (H);1.082,.999(D)</td>
<td></td>
</tr>
<tr>
<td>Vib. = 6 Clear=.445,.499 (H);1.082,.999(D)</td>
<td></td>
</tr>
<tr>
<td>Vib. = 6 Clear=.445,.499 (H);1.183,1.075(D)</td>
<td>3.72736 , 4.05442 , 4.33001</td>
</tr>
<tr>
<td>Total</td>
<td>1.97997</td>
</tr>
<tr>
<td>Mean</td>
<td>1.97997</td>
</tr>
</tbody>
</table>

As can be seen from Table 5 capacity increased with clearance opening which was also predicted by dimensional analysis for cylindrical roller sorters (Section A.3).

B.2 Grid shaker sorter

Figure 22 shows the regression curve for the sorting capacity of the grid shaker sorter. The rate of sorting uniformly increased with the intensity of vibration as seen from the minimal scatter of points.

Vibration intensity less than dial setting corresponding to number 6 position was not strong enough to propel the crawfish from hopper to shaker tray to the sorter outlets. This may be partly explained by the fact that the shaker tray is positioned flat in the horizontal plane. With some inclination it
is possible to sort the crawfish even at low vibration settings although the rate would not be fast enough.

Representative points may be drawn from Table 6 to show positive slopes for capacity as a function of intensity of vibration or spacing between parallel bars or tubes.

Figure 22. Prediction curve for grid shaker sorter capacity.

Pred. eqn.: $Y = 0.1099X^3 - 2.71X^2 + 22.3018X - 57.3075$
\[
\frac{\partial c}{\partial v} \bigg|_{v=\text{const.}} = \frac{(2.59924 - 2.48677)}{(2.14 - 1.96)} = 0.62483 \text{ kg/min per cm increase in the parallel tube or bar spacing.}
\]

\[
\frac{\partial c}{\partial v} \bigg|_{c=\text{const.}} \approx \frac{(2.96235 - 2.48677)}{(8 - 6)} = 0.23779 \text{ kg/min per upward shift in vibration intensity setting.}
\]

As in the cylindrical roller sorter, capacity and either spacing or intensity of vibration have sigmoid-type of curves.

Table 6. Variation in capacity with intensity of vibration and clearance between PVC tubes of the grid shaker sorter.

<table>
<thead>
<tr>
<th>Intensity of vibration</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
<th>Average clearance between parallel PVC tubes, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.96</td>
</tr>
<tr>
<td>6</td>
<td>2.48677</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>2.59924</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.96235</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.70959</td>
<td>5.79</td>
</tr>
<tr>
<td>Total</td>
<td>9.15871</td>
<td>12.73</td>
</tr>
<tr>
<td>Mean</td>
<td>3.05283</td>
<td>4.24</td>
</tr>
</tbody>
</table>

**B.3 Diverging vane-belt sorter**

Figure 23 shows the polynomial fit for the diverging vane-belt sorter. The curve is sigmoid in shape, indicating an inflection point in the neighborhood of 12 to 16 m/min. There can be seen a wide scatter of points.
although the general character of the graph points to a positive correlation between belt speed and sorting capacity. This was earlier predicted by dimensional analysis (Section A.3) where capacity was found to be directly proportional to belt speed \( V \).

Compared to the cylindrical roller sorter the diverging vane belt sorter has one more additional variable which is the belt included angle \( \alpha \). Initial tests showed that the belt clearance requirement was slightly greater than that for the cylindrical roller sorter. Also, to stabilize crawfish flow from hopper the intensity of vibration was adjusted to number 7 setting. Table 7 through Table 12 give the variation in capacity of the diverging vane belt sorter with fixed levels of hopper opening height, vibration intensity, included angle, clearance and belt speed.

The general functional relationship may be treated as a surface

\[
f(c, \text{vel}, v, \alpha, \text{cl}, h) = 0 \tag{57}
\]

where \( c \) is capacity \( \text{vel} \) is the belt speed, \( v \) is the intensity of vibration, \( \alpha \) is the included angle of the V-section, \( \text{cl} \) is clearance between the moving belts and \( h \) is the hopper opening height.

Taking representative data from the aforementioned tables we have the following approximate expressions for rates of change of capacity with respect to \( \text{vel}, v, \alpha, \text{cl}, \) and \( h \):
\[
\frac{\partial c}{\partial v} \bigg|_{h=\text{const.}} = \frac{(4.83 - 2.47)/(7 - 5)}{1} = 1.18 \text{ kg/min per upward shift in intensity of vibration;}
\]

Figure 23. Prediction curve for the diverging vane belt sorter capacity.
\[ \frac{\partial c}{\partial c_{1}} \bigg|_{v,h=\text{const.}} = \frac{(3.42 - 2.42)}{2.55} = 0.39116 \text{ kg/min per percentage increase in clearance dimensions; and,} \]

\[ \frac{\partial c}{\partial h} \bigg|_{c=\text{const.}} = \frac{(2.62 - 2.42)}{(3 - 2.5)} = 0.1574 \text{ kg/min per cm increase in hopper.} \]

\[ \frac{\partial c}{\partial \alpha} \bigg|_{\text{vel.,cl=const.}} = \frac{(2.33 - 3.25)}{(110 - 80.12)} = -0.03079 \text{ kg/min per degree widening of the V-section included angle; this represented a decrease in capacity over the given range. For the range } 80.12 \text{ to } 90^\circ \text{ the capacity increased, a trend which was also predicted by dimensional analysis (Appendix).} \]

Table 7. Variation in capacity with belt speed, hopper opening, included angle, and vibration intensity of the diverging vane belt sorter (part 1).

<table>
<thead>
<tr>
<th>Belt speed, m/min</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=2½ in. Vib.=6</td>
</tr>
<tr>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td>4.94</td>
<td></td>
</tr>
<tr>
<td>5.44</td>
<td></td>
</tr>
<tr>
<td>7.35</td>
<td></td>
</tr>
<tr>
<td>9.06</td>
<td>3.42</td>
</tr>
<tr>
<td>10.07</td>
<td></td>
</tr>
<tr>
<td>10.88</td>
<td></td>
</tr>
</tbody>
</table>
Table 8. Variation in capacity with belt speed, hopper opening, included angle, and vibration intensity of the diverging vane belt sorter (part 2).

<table>
<thead>
<tr>
<th>Belt speed, m/min</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=2½ in. a=80.12° C1=0.7375H-1.21875D in.</td>
</tr>
<tr>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td>4.94</td>
<td></td>
</tr>
<tr>
<td>5.44</td>
<td></td>
</tr>
<tr>
<td>7.35</td>
<td></td>
</tr>
<tr>
<td>9.06</td>
<td>2.42</td>
</tr>
<tr>
<td>10.07</td>
<td></td>
</tr>
<tr>
<td>10.88</td>
<td>4.83</td>
</tr>
<tr>
<td>13.60</td>
<td></td>
</tr>
<tr>
<td>13.71</td>
<td></td>
</tr>
<tr>
<td>15.11</td>
<td>3.19</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 9. Variation in capacity with included angle, hopper opening, intensity of vibration, clearance, and belt speed of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Vane belt included angle</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td>h=2½&quot; Vib.=6</td>
<td>h=2½&quot; Vib.=7</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.84</td>
</tr>
<tr>
<td>Mean</td>
<td>2.92</td>
</tr>
</tbody>
</table>
Table 10. Variation in capacity with hopper opening, intensity of vibration, clearance, and belt speed of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Hopper Opening, in.</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vib.=7 α = 90°</td>
<td>3.23 2.42 2.42 3.25</td>
</tr>
<tr>
<td>Vib.=7 α = 110°</td>
<td>3.80 2.62 2.62 3.25</td>
</tr>
<tr>
<td>Cl=0.734 37H:1.10</td>
<td>937D in. α = 110° Vib.=7</td>
</tr>
<tr>
<td>Speed approx. = 3.23</td>
<td>5.05 4.33 4.83 4.83</td>
</tr>
<tr>
<td>Cl approx. = 2.47</td>
<td>4.22 2.42 2.42 2.47</td>
</tr>
</tbody>
</table>

Total 11.86 12.59 7.37 7.45 4.89 5.58

Mean 3.95 4.19 2.45 3.72 2.44 2.79

Table 11. Variation in capacity with intensity of vibration, included angle, clearance, and belt speed of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Vibration setting</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td>α=80.12° Cl=0.737</td>
<td>2.47 2.33 2.33 2.47 2.33</td>
</tr>
<tr>
<td>5H-1.21875 D h=2½&quot;</td>
<td>2.33 2.33 2.33 2.47 2.47</td>
</tr>
<tr>
<td>α=90° Cl=0.734 37H-</td>
<td>1.10937 D h=4&quot; α=110° Cl=0.734 37H-1.10937 D</td>
</tr>
<tr>
<td>m/min=9.06 Cl=0.734</td>
<td>37H-1.10937 D Speed approx. = 2.33 Cl approx. = 2.33</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 12. Variation in capacity with clearance, hopper opening, included angle, and intensity of vibration.

<table>
<thead>
<tr>
<th>Clearance, in.</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
<th>Clearance, in.</th>
<th>Capacity in kg/min at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=2½&quot;Vib.=6</td>
<td>h=2½&quot;Vib.=7</td>
<td>h=4&quot;Vib.=7</td>
</tr>
<tr>
<td>0.59375H-1.125D</td>
<td>3.23</td>
<td>5.05</td>
<td>3.23</td>
</tr>
<tr>
<td>0.73437H-1.10937D</td>
<td>2.42</td>
<td>4.83</td>
<td>4.83</td>
</tr>
<tr>
<td>0.7375H-1.21875D</td>
<td>3.42</td>
<td>3.19</td>
<td>3.25</td>
</tr>
<tr>
<td>Total</td>
<td>5.84</td>
<td>13.47</td>
<td>18.22</td>
</tr>
<tr>
<td>Mean</td>
<td>2.92</td>
<td>3.36</td>
<td>4.55</td>
</tr>
</tbody>
</table>
C. Grochowicz coefficient of separability $\lambda$

Three sets of programs were developed to calculate and make intraclass comparisons on the coefficients of separability for each individual sorting machine in the study.

Overall, the descending order of magnitude for coefficient of separability for all three sorting machines in the study was as follows: cylindrical roller sorter, diverging vane-belt sorter, and grid shaker sorter with average values of 63.38%, 50.20%, and 44.64%, respectively.

This analysis demonstrated that the degree of separation was high between two widely differentiated classes (e.g. peeler vs. jumbo) whereas the converse is true: geometrically proximal size groups tended to have a lower separation (e.g. peeler vs. medium).

C.1 Cylindrical roller sorter

Program IYCRS (1 through 6 in the set) computed the coefficient of separability $\lambda$ for the cylindrical roller sorter. It considered intraclass comparisons for a 15 x 4 matrix with columns (4) representing size groups of peeler, medium, large, and jumbo while rows (15) represented sample replication.

Table 13 and Table 14 is a summary of the computed $\lambda$s for the left and right pair of rollers which shows the intraclass variation in the data.
Table 13. Comparison table for coefficients of separability for the left pair of roller and four size classes of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93.33</td>
<td>93.33</td>
<td>100.00</td>
<td>53.33</td>
<td>33.33</td>
<td>13.33</td>
<td>386.65</td>
<td>64.44</td>
</tr>
<tr>
<td>2</td>
<td>60.00</td>
<td>93.33</td>
<td>100.00</td>
<td>0.00</td>
<td>-6.67</td>
<td>-6.67</td>
<td>239.99</td>
<td>39.99</td>
</tr>
<tr>
<td>3</td>
<td>46.67</td>
<td>93.33</td>
<td>93.33</td>
<td>20.00</td>
<td>73.33</td>
<td>60.00</td>
<td>386.66</td>
<td>64.44</td>
</tr>
<tr>
<td>4</td>
<td>66.67</td>
<td>73.33</td>
<td>86.67</td>
<td>26.67</td>
<td>66.67</td>
<td>40.00</td>
<td>360.01</td>
<td>60.00</td>
</tr>
<tr>
<td>5</td>
<td>53.33</td>
<td>86.67</td>
<td>93.33</td>
<td>40.00</td>
<td>80.00</td>
<td>66.67</td>
<td>420.00</td>
<td>70.00</td>
</tr>
<tr>
<td>6</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>93.33</td>
<td>100.00</td>
<td>100.00</td>
<td>593.33</td>
<td>98.88</td>
</tr>
<tr>
<td>Total</td>
<td>420.00</td>
<td>539.90</td>
<td>573.55</td>
<td>233.33</td>
<td>346.66</td>
<td>273.33</td>
<td>2386.7</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>70.00</td>
<td>89.99</td>
<td>95.55</td>
<td>38.88</td>
<td>57.77</td>
<td>45.55</td>
<td>66.29</td>
<td></td>
</tr>
</tbody>
</table>

P=peeler; M=medium; L=large; J=jumbo

Table 14. Comparison table for coefficients of separability for the right pair of roller and four size classes of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86.67</td>
<td>93.33</td>
<td>100.00</td>
<td>40.00</td>
<td>60.00</td>
<td>-6.67</td>
<td>373.33</td>
<td>62.22</td>
</tr>
<tr>
<td>2</td>
<td>100.00</td>
<td>93.33</td>
<td>100.00</td>
<td>26.67</td>
<td>40.00</td>
<td>13.33</td>
<td>373.33</td>
<td>62.22</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>53.33</td>
<td>80.00</td>
<td>13.33</td>
<td>80.00</td>
<td>66.67</td>
<td>293.33</td>
<td>48.88</td>
</tr>
<tr>
<td>4</td>
<td>-33.33</td>
<td>53.33</td>
<td>53.33</td>
<td>26.67</td>
<td>73.33</td>
<td>80.00</td>
<td>253.33</td>
<td>42.22</td>
</tr>
<tr>
<td>5</td>
<td>33.33</td>
<td>86.67</td>
<td>100.00</td>
<td>20.00</td>
<td>66.67</td>
<td>0.00</td>
<td>306.67</td>
<td>51.11</td>
</tr>
<tr>
<td>6</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>80.00</td>
<td>580.00</td>
<td>96.66</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 15 and Table 16 show the variation in separability $\lambda$ at fixed levels of hopper opening, cylindrical roller clearance and intensity of vibration. The following observations may be made:

1) Separability increased with rpm, peaked at 40.5 rpm and then fell off at 46 rpm;
2) Separability increased with hopper opening, registering the highest value of 97.77% at 3 in;
3) Separability increased with vibration intensity, recording a maximum at setting number 6;
4) Separability increased with roller clearance having the best results at a narrow end spacing of 0.445/0.499 in. and wide end spacing of 1.183/1.075 in.

Table 15. Variation of $\lambda$ with rpm, hopper opening, and intensity of vibration of the cylindrical roller sorter.
Table 16. Variation of $\lambda$ with hopper opening, clearance setting and intensity of vibration of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th>Hopper opening, h in</th>
<th>Coefficient of separability $\lambda$ at fixed levels of the variables indicated in the column below (test number in parenthesis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vib. = 4.5 Clear=.445,.499(H);1.082,999(D)</td>
</tr>
<tr>
<td>3</td>
<td>56.66</td>
</tr>
<tr>
<td>6</td>
<td>51.11</td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>56.66</td>
</tr>
<tr>
<td>Mean</td>
<td>56.66</td>
</tr>
</tbody>
</table>
C.2 Grid shaker sorter

Program IYGSS (1 through 7 and 9 through 11 in the set) computed the coefficient of separability $\lambda$ for the grid shaker sorter. The process employed columnwise sorting of a $28 \times 2$ matrix with columns (2) representing size groups small and large while rows (28) represented sample replication. The program made corrections for intraclass repetition of values.

Table 17 summarizes the $\lambda$ values obtained from the sample data with two size categories: small and large.

Operating conditions corresponding to tests 1, 2, and 10 gave comparatively higher coefficients of separabilities.

Table 17. Summary of coefficients of separability $\lambda$ for the grid shaker sorter.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Coefficient of separability $\lambda$</th>
<th>Total</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>60.7</td>
<td>67.9</td>
<td>128.60</td>
</tr>
<tr>
<td>2</td>
<td>67.9</td>
<td>32.1</td>
<td>100.00</td>
</tr>
<tr>
<td>3</td>
<td>42.9</td>
<td>25.0</td>
<td>67.90</td>
</tr>
<tr>
<td>4</td>
<td>50.0</td>
<td>10.7</td>
<td>60.70</td>
</tr>
<tr>
<td>5</td>
<td>46.4</td>
<td>32.1</td>
<td>78.50</td>
</tr>
<tr>
<td>6</td>
<td>60.7</td>
<td>25.0</td>
<td>85.70</td>
</tr>
<tr>
<td>7</td>
<td>71.4</td>
<td>7.1</td>
<td>78.50</td>
</tr>
<tr>
<td>9</td>
<td>53.6</td>
<td>39.3</td>
<td>92.90</td>
</tr>
<tr>
<td>10</td>
<td>60.7</td>
<td>42.9</td>
<td>103.60</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 18 shows the variation of the coefficient of separability $A$ at fixed levels of intensity of vibration and spacing between parallel bars or tubes. The following observations may be made:

1) The pattern of increase of separability with parallel tube spacing was bow-shaped in which the maximum occurred at a spacing of 2.14 cm;

2) The same bow-shaped trend existed between separability and spacing between parallel tubes; however, maximum separability was recorded at a spacing of 2.34 cm, corresponding to a vibration of 6.

Table 18. Variation of $A$ with clearance setting and intensity of vibration of the grid shaker sorter.

<table>
<thead>
<tr>
<th>Intensity of vibration</th>
<th>Coefficient of separability $A$ at fixed levels of the variables indicated below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average clearance between parallel PVC tubes, cm</td>
</tr>
<tr>
<td></td>
<td>1.96</td>
</tr>
<tr>
<td>6</td>
<td>57.80</td>
</tr>
</tbody>
</table>

(table con’d.)
C.3 Diverging vane belt sorter

Program IYVBS (4 through 9 and 11 through 15 in the set) computed the coefficient of separability $\lambda$ for the diverging vane belt sorter. Program structure was similar to IYCRS except that comparisons were done for one row of outlets as against a double row in the case of the cylindrical roller sorter.

Operating conditions corresponding to tests 4 and 15 gave the highest coefficients of separability.

Table 19 shows the computed $\lambda$s which include intrasize comparisons for four size categories or groups.

**Table 19. Comparison table for coefficient of separability for four size classes of the diverging vane belt sorter**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Size group comparisons</th>
<th>Total</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P vs. M</td>
<td>P vs. L</td>
<td>P vs. J</td>
</tr>
<tr>
<td>4</td>
<td>80.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>5</td>
<td>6.67</td>
<td>40.00</td>
<td>100.00</td>
</tr>
<tr>
<td>6</td>
<td>-40.00</td>
<td>33.33</td>
<td>86.67</td>
</tr>
</tbody>
</table>

(table con'd.)
Table 20 through Table 25 show the variation of the coefficient of separability $\lambda$ at fixed levels of the following variables: belt speed, hopper opening height, intensity of vibration, included angle of the V-section of the belt, and clearance between belts.

The following observations may be deduced from the data:

1) Separability generally increased with belt speed up to a certain maximum point and then diminished; there existed some of scattering of points suggesting that the sorting process was quite sensitive to small changes in the input variables;

2) Belt speed range 7.35 to 13.6 fpm appeared to give the best
separability although belt speed as high as 18.83 fpm gave fair results;

3) Separability was high at an intensity of vibration setting of 7;

4) Separability was high at hopper opening height equal to 4 in.;

5) Separability was high at an included angle equal to 110° only if hopper opening height was adjusted to 4 in and vibration intensity was set at number 7.

6) Separability was best at clearance settings equal to 0.7375 in. at the narrow end and 1.21875 in at the wide end.

Table 20. Variation λ with belt speed, hopper opening, included angle, and intensity of vibration for the diverging vane belt sorter (part 1).

<table>
<thead>
<tr>
<th>Belt speed, m/min</th>
<th>Coefficient of separability λ at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=2½ in. Vib.=6</td>
</tr>
<tr>
<td>4.20</td>
<td>47.77</td>
</tr>
<tr>
<td>5.44</td>
<td>44.44</td>
</tr>
<tr>
<td>7.35</td>
<td>95.55</td>
</tr>
<tr>
<td>9.06</td>
<td>37.77</td>
</tr>
<tr>
<td>10.07</td>
<td>32.22</td>
</tr>
<tr>
<td>10.88</td>
<td>40.00</td>
</tr>
<tr>
<td>13.60</td>
<td>92.20</td>
</tr>
<tr>
<td>13.71</td>
<td>21.10</td>
</tr>
<tr>
<td>15.11</td>
<td>58.89</td>
</tr>
<tr>
<td>18.33</td>
<td>65.55</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 21. Variation of $\lambda$ with belt speed, hopper opening, included angle, and intensity of vibration for the vane belt sorter (part 2).

<table>
<thead>
<tr>
<th>Belt speed, m/min</th>
<th>$h=2^{1/2}$ in.</th>
<th>$h=4$ in.</th>
<th>$\alpha=60.12^\circ$</th>
<th>$h=4$ in.</th>
<th>$\alpha=90^\circ$</th>
<th>$h=4$ in.</th>
<th>$\alpha=110^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha=80.12^\circ$</td>
<td>$C_l=0.7375H$</td>
<td>$-1.21875D$ in.</td>
<td>$C_l=0.73437H$</td>
<td>$-1.10937D$ in.</td>
<td>$C_l=0.73437H$</td>
<td>$-1.10937D$ in.</td>
</tr>
<tr>
<td></td>
<td>$Vib.=7$</td>
<td>$Vib.=7$</td>
<td>$Vib.=5$</td>
<td>$Vib.=5$</td>
<td>$Vib.=7$</td>
<td>$Vib.=7$</td>
<td>$Vib.=7$</td>
</tr>
<tr>
<td>4.94</td>
<td>44.44</td>
<td>37.77</td>
<td>37.77</td>
<td>37.77</td>
<td>37.77</td>
<td>37.77</td>
<td>37.77</td>
</tr>
<tr>
<td>5.44</td>
<td>95.55</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
<td>40.00</td>
</tr>
<tr>
<td>7.35</td>
<td>13.60</td>
<td>58.89</td>
<td>58.89</td>
<td>58.89</td>
<td>58.89</td>
<td>58.89</td>
<td>58.89</td>
</tr>
<tr>
<td>9.06</td>
<td>10.07</td>
<td>65.55</td>
<td>65.55</td>
<td>65.55</td>
<td>65.55</td>
<td>65.55</td>
<td>65.55</td>
</tr>
<tr>
<td>Total</td>
<td>198.88</td>
<td>77.77</td>
<td>101.33</td>
<td>87.77</td>
<td>54.44</td>
<td>174.42</td>
<td>102.21</td>
</tr>
<tr>
<td>Mean</td>
<td>66.29</td>
<td>25.92</td>
<td>34.44</td>
<td>43.89</td>
<td>27.22</td>
<td>58.14</td>
<td>34.07</td>
</tr>
</tbody>
</table>
Table 22. Variation of $\lambda$ with included angle, hopper opening, intensity of vibration, clearance, and belt speed of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Vane belt included angle</th>
<th>Coefficient of separability $\lambda$ at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=2½&quot; Vib.=6</td>
</tr>
<tr>
<td></td>
<td>h=2½&quot; Vib.=7</td>
</tr>
<tr>
<td></td>
<td>h=4&quot; Vib.=7</td>
</tr>
<tr>
<td></td>
<td>Cl=0.73 437H;1.10937D Vib.=5</td>
</tr>
<tr>
<td></td>
<td>Cl=0.73 437H;1.10937D Vib.=7</td>
</tr>
<tr>
<td></td>
<td>m/min=9.06 Cl=0.73 437H;1.10937D Vib.=7 Speed approx.</td>
</tr>
<tr>
<td></td>
<td>approx.</td>
</tr>
<tr>
<td>80.12</td>
<td>95.55</td>
</tr>
<tr>
<td></td>
<td>58.89</td>
</tr>
<tr>
<td></td>
<td>44.44</td>
</tr>
<tr>
<td>90</td>
<td>21.10</td>
</tr>
<tr>
<td></td>
<td>32.22</td>
</tr>
<tr>
<td></td>
<td>40.00</td>
</tr>
<tr>
<td></td>
<td>40.00</td>
</tr>
<tr>
<td>110</td>
<td>37.77</td>
</tr>
<tr>
<td></td>
<td>65.55</td>
</tr>
<tr>
<td></td>
<td>92.20</td>
</tr>
<tr>
<td></td>
<td>16.67</td>
</tr>
<tr>
<td></td>
<td>47.77</td>
</tr>
<tr>
<td></td>
<td>37.77</td>
</tr>
<tr>
<td></td>
<td>16.67</td>
</tr>
<tr>
<td>Total</td>
<td>132.88</td>
</tr>
<tr>
<td></td>
<td>156.66</td>
</tr>
<tr>
<td></td>
<td>197.75</td>
</tr>
<tr>
<td></td>
<td>16.67</td>
</tr>
<tr>
<td></td>
<td>87.77</td>
</tr>
<tr>
<td></td>
<td>37.77</td>
</tr>
<tr>
<td></td>
<td>61.11</td>
</tr>
<tr>
<td>Mean</td>
<td>66.44</td>
</tr>
<tr>
<td></td>
<td>39.17</td>
</tr>
<tr>
<td></td>
<td>65.92</td>
</tr>
<tr>
<td></td>
<td>16.67</td>
</tr>
<tr>
<td></td>
<td>43.89</td>
</tr>
<tr>
<td></td>
<td>37.77</td>
</tr>
<tr>
<td></td>
<td>30.56</td>
</tr>
</tbody>
</table>

Table 23. Variation of $\lambda$ with hopper opening, intensity of vibration, clearance, and belt speed of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Hopper Opening, in.</th>
<th>Coefficient of separability $\lambda$ at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vib.=7 $\alpha=90^0$</td>
<td>Cl=0.734 37H;1.10 937D in. $\alpha=110^0$ Vib.=7</td>
</tr>
<tr>
<td>Vib.=7 $\alpha=110^0$</td>
<td>Cl=0.734 37H;1.10 937D in. $\alpha=110^0$ Vib.=7</td>
</tr>
<tr>
<td>Cl=0.734 37H;1.10 937D in. $\alpha=110^0$ Vib.=7</td>
<td>Cl=0.734 37H;1.10 937D in. $\alpha=110^0$ Vib.=7</td>
</tr>
<tr>
<td>Speed approx. =</td>
<td>Speed approx. =</td>
</tr>
<tr>
<td>Speed approx. =</td>
<td>Speed approx. =</td>
</tr>
<tr>
<td>Speed approx. =</td>
<td>Speed approx. =</td>
</tr>
<tr>
<td>Speed approx. =</td>
<td>Speed approx. =</td>
</tr>
<tr>
<td>Speed approx. =</td>
<td>Speed approx. =</td>
</tr>
<tr>
<td>Speed approx. =</td>
<td>Speed approx. =</td>
</tr>
<tr>
<td>(table con'd.)</td>
<td>(table con'd.)</td>
</tr>
</tbody>
</table>
Table 24. Variation of $\lambda$ with intensity of vibration, included angle, belt clearance, and belt speed of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Vibration setting</th>
<th>Coefficient of separability $\lambda$ at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha=80.12^\circ$ 0.737 $37H$ $\beta=2.1875$ 1.21875</td>
</tr>
<tr>
<td></td>
<td>$\alpha=90^\circ$ 0.734 $37H$ $\beta=4^\circ$</td>
</tr>
<tr>
<td></td>
<td>$\alpha=110^\circ$ 0.734 $37H$ $\beta=4^\circ$</td>
</tr>
<tr>
<td></td>
<td>$\alpha=110^\circ$ 0.734 $37H$ $\beta=4^\circ$</td>
</tr>
<tr>
<td></td>
<td>$m/min=9$ 5.06 37H $\beta=1.0937$</td>
</tr>
<tr>
<td></td>
<td>Speed approx. =</td>
</tr>
<tr>
<td></td>
<td>5 16.67 16.67 16.67</td>
</tr>
<tr>
<td></td>
<td>6 95.55 37.77 37.77</td>
</tr>
<tr>
<td></td>
<td>7 44.44 58.89 40.00 65.55 92.20 47.77 44.44</td>
</tr>
<tr>
<td></td>
<td>Total 198.88 40.00 174.42 102.21 37.77 61.11</td>
</tr>
<tr>
<td></td>
<td>Mean 66.29 40.00 58.14 34.07 37.77 30.56</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 25. Variation of $\lambda$ with clearance, hopper opening, included angle, and intensity of vibration of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Clearance, in.</th>
<th>Coefficient of separability $\lambda$ at fixed levels of the variables indicated in the column below</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h=2½&quot; Vib.=6</td>
</tr>
<tr>
<td>0.59375 H-1.125D</td>
<td>21.10 32.22 65.55</td>
</tr>
<tr>
<td>0.73437 H-1.10937 D</td>
<td>37.77</td>
</tr>
<tr>
<td>0.7375H-1.21875 D</td>
<td>95.55 44.44 95.55</td>
</tr>
<tr>
<td>Total</td>
<td>133.32 156.55 293.30</td>
</tr>
<tr>
<td>Mean</td>
<td>66.66 39.14 97.77</td>
</tr>
</tbody>
</table>

D. Vibration analysis

During the tests forced vibration played a key role in regulating the flow of crawfish from the hopper to the sorting chamber. For the cylindrical roller sorter and the diverging vane belt sorter flow of crawfish was made more or less uniform by vibrating an aluminum hopper of a fixed design by means of an eccentric motor located underneath. The detachable hopper assembly weighed 19.54768 kg while the PVC parallel bars weighed 4.53514 kg.
Therefore, at any time during the tests the active load of vibration was as follows:

For the cylindrical roller sorter and diverging vane belt sorter,

Total Load = 19.54768 + Weight of crawfish.

For the grid shaker sorter,

Total load = 17.91382 + Weight of crawfish.

A damped dynamic vibration absorber system was used to model hopper vibration as shown schematically below (Figure 24):

![Diagram of spring-mass-damper system](image)

Figure 24. Spring-mass-damper system.
The equations of motion may be written as follows:

\[ m_1 x''_1 + k_1 x_1 + k_2 (x_1 - x_2) + c_2 (x'_1 - x'_2) = F_0 \sin \omega t \]  \hfill (58)

\[ m_2 x''_2 + k_2 (x_2 - x_1) + c_2 (x'_2 - x'_1) = 0 \]  \hfill (59)

By assuming the solution to be

\[ x_j(t) = X_j e^{i\omega t}, \quad j = 1, 2 \]  \hfill (60)

the solution can be obtained as follows:

\[ X_1 = \frac{F_0 (k_2 - m_2 \omega^2 + ic_2 \omega)}{[\left(k_1 - m_1 \omega^2 \right) \left(k_2 - m_2 \omega^2 \right) - m_2 k_2 \omega^2] + i\omega c_2 (k_1 - m_1 \omega^2 - m_2 \omega^2)}^{-1} \]  \hfill (61)

\[ X_2 = \left[X_1 (k_2 + i\omega c_2)\right] [k_2 - m_2 \omega^2 + i\omega c_2]^{-1} \]  \hfill (62)

Some terms could be grouped together as follows:

\[ \mu = m_2/m_1 \quad \text{(mass ratio)} \]
\[ \delta_0 = F_0/k_1 \quad \text{(static deflection of the system)} \]
\[ \omega_s^2 = k_2/m_2 \quad \text{(square of natural frequency of absorber)} \]
\[ \omega_n^2 = k_1/m_1 \quad \text{(square of natural frequency of main mass)} \]
\[ \zeta = \frac{c_d}{c} \] 
(damping ratio)

\[ f = \frac{\omega_d}{\omega_n} \] 
(ratio of natural frequencies)

\[ g = \frac{\omega}{\omega_n} \] 
(forced frequency ratio)

Rewriting \( X_1 \) and \( X_2 \) in terms of these variables,

\[
X_1 = \left[ (2^g g^2 + (g^2-f^2)^2 \right] \left[ ((2^g g^2 - 1 + u g^2 + c_1 (f^2 - g^2)^2 + (u f^2 g^2 + (g^2-1)(g^2-f^2))^2 \right]^{1/2} 
\]

\[ 2c_1 \xi g^2 (k_1 m_1)^{1/2})^2 \]

\[ X_2 = X_1 \left( \frac{f^2 + 2g^2 \xi}{f^2 - g^2 + 2g^2} \right) \] 

(63)

(64)

Program GSSVIB modeled hopper behavior as a 2 degree of freedom spring-mass-damper system as described by the equations above. It calculated the amplitudes for the range of mass ratios (hopper contents emptying out) encountered in the tests.

**D.1 Cylindrical roller sorter**

Of the motor vibration the following was observed: favorable \( z \)-coordinate displacement occurred at a setting greater than 4.5 (lower settings generated unfavorable cross-axes displacements). When fully loaded a motor setting of 6 seemed to be the best in respect to promoting smooth sliding of crawfish without clumping.

When the hopper was fully loaded and set at the upper range of number 11 the recorded maximum amplitudes went slightly over 0.50 cm. Since the
hopper was made of sheet metal part of the observed amplitude was due to natural flexing of the material. It was difficult to isolate pure displacement due to vibration. Nonetheless, program GSSVIB satisfactorily predicted the range of amplitudes which was 0.00243 m for $x_1$ (hopper assembly) and 0.00864 m for $x_2$ (crawfish in the hopper). This was at a mass ratio approaching unity.

It is of interest to note that damping coefficient for the crawfish material was found to be approximately 64 N·sec/m (at $\xi = 0.046$, $g = 0.14$, and $f = 0.12$). This was obtained by working GSSVIB backwards until the parameter values satisfied the modelling equations.

Since crawfish is not smooth-flowing unlike most granular materials it was difficult to adjust the sliding gate; however, a noticeable change in flow was observed when the sliding gate was varied by increments of one-third of the height of the hopper opening (total height of the hopper sliding gate was 23.02 cm), as specified by program BIOPHYS.

**D.2 Grid shaker sorter**

For the grid shaker sorter vibration was the motive power for size separation; crawfish dropped into equally spaced parallel PVC tubes which was agitated by the vibrator motor.

Amplitudes of vibration were measured using a direct reading Vernier scale using the edges of the shaker tray as reference axis (x along the longitudinal axis of the parallel tubes). Table 26 shows the incremental displacement of the space coordinates at fixed levels of vibration intensity. The
values typify a forward rolling motion of the shaker tray with slight wiggling at the sides. Toward higher frequencies the measured displacement decreased.

Table 26. Peak-to-peak displacement (in.) of the grid shaker sorter tray at the intensity of vibration indicated.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Intensity of vibration (dial gage setting)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Δx</td>
<td>0.06250</td>
</tr>
<tr>
<td>Δy</td>
<td>0.02080</td>
</tr>
<tr>
<td>Δz</td>
<td>0.09575</td>
</tr>
</tbody>
</table>

Program GSSVIB predicted vertical amplitudes which were well within these experimental values at mass ratios approaching one-half (maximum crawfish weight always half the weight of the shaker tray assembly). Compared to the cylindrical roller sorter the active mass center was very much lower, hence, the displacements observed were of a lower magnitude. The dynamic change in amplitudes, however, required more elaborate instrumentation and this was beyond the scope of the study.

D.3 Diverging vane-belt sorter

Requirements for vibration adjustment closely followed that of the cylindrical roller sorter. The narrower opening of the V-belts meant that hopper opening area needed to be set vertically first before adjusting hopper opening. Still the vibration amplitudes did not differ to a great extent.
E. Optimum spacing based on Peleg's criteria

Program OPDPEL was written to determine the optimum spacing of the cylindrical roller sorter based on Peleg's (1985) criteria. Computer iterations determined sorting efficiency and loss based on the following variables: ideal and actual frequency distribution of the differentiating characteristics (i.e., weight and bodily dimensions), economic weighting factor or relative pricing between classes, and off-grade counts among size classes.

It was assumed that the distribution of sample weights among classes or sizes was normal and that their standard deviations were approximately equal. Thus, it was possible to take averages between adjacent spacing or dimensions in the cylindrical roller sorter as set of optimal dimension.

Regarding the pricing between crawfish sizes season averages were used although this kept on changing during the season itself. To be on the conservative side a uniformly progressive price gradation was assumed for peeler, medium, and large sizes. For the jumbo size it was assumed to be five times as expensive as peelers (premium price paid by Swedish importers).

Table 27 lists the losses during sorting in the form of damaged crawfish, slippage, or crawfish which did not pass through sorter outlets. Losses were not recorded for the grid shaker sorter because all crawfish passed through the two sorter outlets (small and large). Both the cylindrical roller sorter and the diverging vane belt sorter required crawfish to pass through a sorting medium which were moving parts driven by motors.
Table 27. Percentage of crawfish which slipped past hopper, got stuck between rollers or crushed between motor gears (sorting loss).

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Cylindrical roller sorter</th>
<th>Diverging vane belt sorter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.287</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.345</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.469</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.505</td>
<td>2.346</td>
</tr>
<tr>
<td>5</td>
<td>0.359</td>
<td>1.794</td>
</tr>
<tr>
<td>6</td>
<td>0.551</td>
<td>2.366</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.545</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>2.032</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>1.996</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>3.153</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>1.224</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>1.028</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>1.624</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>0.989</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>0.926</td>
</tr>
<tr>
<td>Total</td>
<td>2.516</td>
<td>20.023</td>
</tr>
<tr>
<td>Mean</td>
<td>0.419</td>
<td>1.66856</td>
</tr>
</tbody>
</table>

Note: Tests for cylindrical roller sorter run from 1 through 6 while tests 1 through 4 in the diverging vane belt sorter were discontinued due to unacceptable sorting; for grid shaker sorter losses were lumped together with collector outlet figures.

Program OPDPEL yielded the following results: (1) under ideal conditions it is expected that sorting efficiency will be in the order of 96.412
% with a sorting loss of 3.588 %; (2) in the actual conditions of the study sorting efficiency was found to be 71.8295 % with a sorting loss of 28.1705 %; (3) there was no departure from the roller spacing which gave the best results, that is, what was found to be the best setting in the experiment was consistent with the computed values from program OPDPEL.

F. Effect of water spray

Water spray was tried in the diverging vane belt sorter to see if it positively affected the sorting process. Initially, the sorter outlet discharge tanks were filled with water. A centrifugal motor pumped water up the hopper via a pair of 2- in PVC pipes. These pipes were drilled with small holes providing 82 water jets angled towards the vane belts surface; water recirculated to the outlet tanks and then to the motor pump. This test was discontinued for the following reasons:

1. A water recirculating system in crawfish sorting caused problems primary of which was the clogging of water spouts due to debris -- this led to irregular flow of water and occasional stoppages;
2. Control of water jet trajectory was difficult, the ideal being water jet directed towards the center of the belt clearance;
3. Sampling after each test was problematic because the discharge tanks had to be emptied of crawfish immediately to prevent oxygen starvation;
4. Water reduced contact friction between crawfish and the belt surface
causing the crawfish to slip over quickly to the next larger sorter outlet; this was observed at about 16.22 ft/min.

With non-recirculating water spray system, better spray pattern control, and operating at lower speeds it is possible for the system to work out, deriving the greater value of cleaner crawfish. Subject to these conditions it is recommended that water flow be from 12 to 15 liter/min.

G. Comparison of the performance of the three crawfish sorting machines

Table 28 shows a summary of the performance parameters of the three crawfish sorting machines in the study. Of the three machines the grid shaker sorter had the lowest separability; it was unable to segregate small from large crawfish to a comparable degree as the cylindrical roller sorter and the diverging vane belt sorter. The cylindrical roller sorter and the diverging vane belt sorter had comparable performance at the optimal range but differed much over the overall range of test conditions. On this basis the cylindrical roller sorter is a more promising type of machine compared to the diverging vane belt sorter being more stable and less subject to wide fluctuations in either separability or capacity. Another reason favoring the use of cylindrical roller sorters is its fewer percentage of losses (Table 27).
Table 28. Performance parameters of the three crawfish sorting machines.

<table>
<thead>
<tr>
<th>Crawfish sorter and Parameter</th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole range</td>
</tr>
<tr>
<td>Cylindrical roller sorter:</td>
<td>63.42 3.59</td>
</tr>
<tr>
<td>1. Separability, %</td>
<td></td>
</tr>
<tr>
<td>2. Capacity, kg/min</td>
<td></td>
</tr>
<tr>
<td>Div. vane belt sorter:</td>
<td>50.19 3.55</td>
</tr>
<tr>
<td>1. Separability, %</td>
<td></td>
</tr>
<tr>
<td>2. Capacity, kg/min</td>
<td></td>
</tr>
<tr>
<td>Grid shaker sorter:</td>
<td>44.64 3.66</td>
</tr>
<tr>
<td>1. Separability, %</td>
<td></td>
</tr>
<tr>
<td>2. Capacity, kg/min</td>
<td></td>
</tr>
</tbody>
</table>

H. Modifications in the existing crawfish sorters

H.1 Cylindrical roller sorter

1. Roller surfaces need to be coated with a thin layer of rubber to increase contact friction; it was observed that motion of crawfish between the helical grooves was sluggish as a result of slippage.

2. Distance of travel between the hopper and the peeler section need to be increased to allow for a longer residence time, thus preventing peeler crawfish from being conveyed to the next larger sections.

3. A more convenient means of adjusting clearance should be incorporated in the machine, perhaps snail-type or spring-loaded latches.
4. Hanger hooks need to be fixed to the underside of the sorter to facilitate attachment and removal of collector sacks.

5. The metal frame should be built with closer tolerances around the roller section of the sorter; crawfish chelae got stuck in this narrow openings causing minor losses and overworking the sorter motors.

**H.2 Diverging vane belt sorter**

1. A more convenient means of adjusting belt angles and clearances should be incorporated in this crawfish sorter; in the present prototype these are adjusted by moving 4 pairs of screws.

2. Sheet metal baffles need to be installed near the narrow clearance of the belt sorter to prevent crawfish falling from the hopper from being entrapped by the motor pulleys.

3. The angle of inclination of the sliding board (towards sorter outlet) need to be increased to at least 30° in order to speed up sliding of crawfish to the sorter discharge compartments.

**H.3 Grid shaker sorter**

1. A more convenient way of adjusting clearance between parallel bars needs to be incorporated in the existing prototype; or, the simplest solution is to use a set of interchangeable, pre-dimensioned tray of parallel bars.

2. Flow of crawfish from hopper to shaker tray is mostly controlled by hand; some means of mechanical metering should be incorporated in this prototype so as not to overwork the operator who is simultaneously spreading out
crawfish in the shaker tray into the desired thickness of the layer.

3. Surfaces close to the discharge ports need to be inclined in order for crawfish to fall more easily towards the collector sacks.
VI. SUMMARY AND CONCLUSION

The following are the main highlights of this study:

1. The weight of newly harvested live and unsorted crawfish had an average \( \% \) CV of 44.02. After sorting the crawfish into four size groups (peeler, medium, large, jumbo) the average \( \% \) CV dropped to 6. This figure was taken from sample crawfish in the cylindrical roller sorter outlets. The diverging vane belt sorter had comparable values for this reduction in \( \% \) CV which was about 86 \( \% \). The grid shaker sorter, having only two outlets, had approximately 56 \( \% \) reduction in \( \% \) CV.

2. Sorting can be achieved by means of size separation based on the bodily dimensions of crawfish, notably carapace width and carapace depth. As to which of the two dimensions is the more influential is difficult to answer. It appeared that if the sorting motion is screw type it would be carapace width as was observed in the cylindrical roller sorter. If, on the other hand, the motion is linear with barely noticeable twisting as was observed in the vane belt sorter, the critical dimension would be carapace depth because crawfish would fall on its underside while taking anchor on the moving flat surface. If the crawfish moves through parallel bars subjected to vigorous shaking as was noted in the grid shaker sorter it would tend to slip past the clearance along its longitudinal axis -- thus separated according to carapace width.

3. Empirical relationships and design data were developed for the more important physical characteristics of crawfish. These were a) bulk density,
particle density, and sliding friction on the two most promising construction materials for sorter machines (PVC and aluminum); b) prediction equations for crawfish weight, total body length, carapace depth and carapace width; and c) verification of the Romaire equation as a valid functional relationship between total body length and body weight (Section IIIA).

4. Expressions for volumetric capacity and torque were found using the technique of dimensional analysis -- this applies for the cylindrical roller sorter and the vane belt sorter. The resulting general equations were found to be self-consistent and are in agreement with past studies. The computer programs written explicitly for this analysis are useful starting points for succeeding studies on sorting. An exhaustive testing of the myriad combinations arising from several grouping of terms was beyond the scope of this study. Nonetheless, a basic framework of analysis was completed.

5. Screw path theory was used to describe crawfish particle motion specifically for cylindrical roller type of sorters. It was beyond the scope of this study, however, to check how it agreed with experimental data in the light of the fact that crawfish motion is far more complex and would go beyond the assumption of single particle motion in the theory. The basic idea in here is perhaps more in the way of indicating to succeeding researchers that it could be refined with appropriate empirical corrections factors. It is a potentially a time-saving technique.

6. The parameter for the calculation of stresses in load-carrying belt sections
was estimated using a computer iteration scheme. With this equation, uniquely defined for crawfish, it is possible to precisely calculate stresses in large sorting systems which use the same mechanism as the diverging vane belt. It is then possible to avoid economically costly downtimes due to failures.

7. A straightforward but effective method was tested for finding the optimum diameter of a cylindrical roller sorter (objective: to minimize crushing forces on crawfish). By pure coincidence the calculated optimum diameter matched exactly the dimension of the cylindrical roller sorter! Not surprisingly, therefore, even when operated above 50 rpm no crawfish got crushed by the rolling forces! Only those crawfish which were pushed toward the narrow gaps in the metal framing got crushed but not in the space between the pair of rollers.

8. Hopper vibration was modelled using a two degree of freedom spring-mass-damper system, technically known as a damper absorber system. Measurements of the amplitude of displacement in all three sorters came quite close to the theoretical predictions. With the great design flexibility and controllability of vibrating systems in regulating flow of sorting materials a modelling scheme is almost axiomatic. It is fair to expect that based on the results of this study an engineer can have a high level of confidence in the one-to-one correspondence between theory and practice. Also, by an indirect approach, and subject to the constraints of the system some useful constants were estimated, e.g., damping coefficient for crawfish. However much it offers
it was observed that the beneficial effect of vibration was limited to a certain range of frequency. This was quite discernible in the grid shaker sorter wherein at some combination of parallel bar spacing and intensity of vibration crawfish bounced back from its initial starting point.

9. The study broke ground in applying the concepts of optimizing cylindrical roller spacing based upon economic and as well as statistical criteria. It is well known that consumers can tolerate a greater or a lesser amount of "off-grades" depending on the economic picture. Thus, a sorting machine can be operated to lay more or less emphasis on a particular grade in cognizance of consumer standards in order to maximize returns. The findings of this study point to a kind of moving average in the matter of attaining target sorting goals: that is, the level of sorting efficiency changes subject to: a) distribution characteristics of the crawfish itself and b) market factors such as price differential per grade. Hence, optimum spacing between, say, sorter rollers is highly correlated to the aforesaid factors.

10. This study established benchmark data on what needs to be the operating conditions in a sorting machine before it can deliver its best; or, alternatively, what could lead to poor results. The tables which follow (Table 29 through 31) give a summary of the operating conditions during the tests with columns both for capacity and separability. Their individual performance ranks were computed by taking the average of their respective capacities and separabilities; these are shown in the next set of tables (Table 32, Table 33,
and Table 34). From here it is possible to mark off non-feasible sets of machine operating conditions and proceed to identify the optimum ranges. The findings in this study demonstrated the sensitivity of the sorting process to the following input machine variables: roller rpm, hopper opening height, intensity of vibration, clearance between rollers or belts or parallel bars, and included angle between belts. The basic thread of relationship between an arbitrary argument and its response variable appears to be what is called a sigmoid function: a positive inflection point followed by a negative inflection point.

11. The study showed that sorting crawfish with water-assist system requires more investment in time and money than may be necessary. If, however, a crawfish processor is willing to bat for the payoff from cleaner crawfish then this study came up with some useful recommendations.

Table 29. Summary of operating conditions, capacity and separability of the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Clearance, in.</th>
<th>Speed, fpm</th>
<th>h, in</th>
<th>Angle, deg.</th>
<th>Vib.</th>
<th>Cap., kg/min (lb/hr)</th>
<th>Coef. of separability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.7375 (H) 1.21875 (D)</td>
<td>24.12</td>
<td>2¼</td>
<td>80.12</td>
<td>6</td>
<td>3.43 (453.60)</td>
<td>95.55</td>
</tr>
<tr>
<td>5</td>
<td>0.7375 (H) 1.21875 (D)</td>
<td>49.58</td>
<td>2½</td>
<td>80.12</td>
<td>7</td>
<td>3.20 (423.26)</td>
<td>58.89</td>
</tr>
<tr>
<td>6</td>
<td>0.7375 (H) 1.21875 (D)</td>
<td>17.85</td>
<td>2½</td>
<td>80.12</td>
<td>7</td>
<td>3.25 (430.19)</td>
<td>44.44</td>
</tr>
<tr>
<td>7</td>
<td>0.59375 (H) 1.125 (D) 47 (R) 43 (L)</td>
<td>2½</td>
<td>90</td>
<td>7</td>
<td>3.24 (428.07)</td>
<td>21.10</td>
<td></td>
</tr>
</tbody>
</table>

(table con'd.)
### Table 30. Summary of operating conditions, capacity and separability of the grid shaker sorter.

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Clearance, cm</th>
<th>Vibration setting</th>
<th>Cap., kg/min (lb/hr)</th>
<th>Coef. of separability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.34</td>
<td>6</td>
<td>2.98 (394)</td>
<td>64.30</td>
</tr>
<tr>
<td>2</td>
<td>2.34</td>
<td>8</td>
<td>4.54 (600)</td>
<td>50.00</td>
</tr>
<tr>
<td>3</td>
<td>2.34</td>
<td>10</td>
<td>3.49 (461.76)</td>
<td>33.95</td>
</tr>
<tr>
<td>4</td>
<td>2.34</td>
<td>7</td>
<td>3.72 (492.24)</td>
<td>30.35</td>
</tr>
</tbody>
</table>

(table con’d.)
Table 31. Summary of operating conditions, capacity and separability of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Clearance, in.</th>
<th>Vibration</th>
<th>Rpm</th>
<th>h, in.</th>
<th>Capacity, kg/min (lb/hr)</th>
<th>Coef of separability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hopper end</td>
<td>Discharge end</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.445</td>
<td>1.082</td>
<td>6</td>
<td>46</td>
<td>4.37 (578.15)</td>
<td>63.33</td>
</tr>
<tr>
<td></td>
<td>0.499</td>
<td>0.999</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.445</td>
<td>1.082</td>
<td>4-6</td>
<td>30-46</td>
<td>3.10 (410.13)</td>
<td>51.10</td>
</tr>
<tr>
<td></td>
<td>0.499</td>
<td>0.999</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.445</td>
<td>1.082</td>
<td>4.5</td>
<td>20</td>
<td>1.98 (261.95)</td>
<td>56.66</td>
</tr>
<tr>
<td></td>
<td>0.499</td>
<td>0.999</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(table con'd.)
Table 32. Combined ranking of coefficient of separability $\lambda$ and capacity of the cylindrical roller sorter.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Coefficient of separability, $\lambda$ (rank in parenthesis)</th>
<th>Capacity, kg/min (rank in parenthesis)</th>
<th>Average rank</th>
<th>Overall rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63.33 (2)</td>
<td>4.36999 (1)</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>97.77 (1)</td>
<td>4.05442 (3)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>60.55 (3)</td>
<td>3.72736 (4)</td>
<td>3.5</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>51.11 (5.5)</td>
<td>4.33001 (2)</td>
<td>3.75</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>56.66 (4)</td>
<td>1.97997 (6)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>51.105 (5.5)</td>
<td>3.10000 (5)</td>
<td>5.25</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 33. Combined ranking of coefficient of separability $\lambda$ and capacity for the grid shaker sorter.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Coefficient of separability, $\lambda$ (rank in parenthesis)</th>
<th>Capacity, kg/min (rank in parenthesis)</th>
<th>Average rank</th>
<th>Overall rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>51.80 (2)</td>
<td>4.35299 (3)</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>50.00 (3)</td>
<td>4.53515 (2)</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>48.20 (4)</td>
<td>5.78587 (1)</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>64.30 (1)</td>
<td>2.97808 (7)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>46.45 (5)</td>
<td>2.59924 (9)</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>42.85 (6)</td>
<td>2.96236 (8)</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>30.35 (10)</td>
<td>3.72063 (4)</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>39.25 (7.5)</td>
<td>3.70960 (5)</td>
<td>6.25</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>33.95 (9)</td>
<td>3.49025 (6)</td>
<td>7.5</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>39.25 (7.5)</td>
<td>2.48677 (10)</td>
<td>8.75</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 34. Combined ranking of coefficient of separability $\lambda$ and capacity for the diverging vane belt sorter.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Coefficient of separability, $\lambda$ (rank in parenthesis)</th>
<th>Capacity, kg/min (rank in parenthesis)</th>
<th>Average rank</th>
<th>Overall rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>92.22 (2)</td>
<td>5.05344 (1)</td>
<td>1.5</td>
<td>1</td>
</tr>
</tbody>
</table>

(table con'd.)
12. A draft of standards for crawfish was prepared to serve as a basis for comparing the performance of crawfish sorting machines. This incorporates the main findings of this study.
VII. RECOMMENDATION

The following are recommended for future study:

1. The crawfish season commences in late December and ends in late April to early May; therefore, tests could be run only at this time. To conduct test runs at any time it might be a good idea to use artificial or dummy crawfish made of rubber or other synthetic material like plastics. The following would be the limitations of this method:

   a) cannot simulate the effect of clumping in sorting pond-fresh live crawfish,
   
   b) cannot accurately reflect the percentage of damaged crawfish,
   
   c) cannot precisely duplicate the surface or frictional characteristics of real crawfish.

On the other hand, its advantages would be:

   a) immediate assessment of the performance of the test sorter prototype,
   
   b) permits repeated tests for multi-factor, multi-variable types of experiments thus reducing the cost of sampling,
   
   c) quick data collection scheme as the dummy crawfish could be color coded for size dimensions and weight by the manufacturer.

2. Sorting studies on crawfish inevitably deal with vibration in some form, primarily for metering or regulating flow. How intense a vibration the crawfish can absorb before it loses its vigor is not known. It was observed that some few
smaller crawfish lost some leg parts when it was vigorously shaken. With bigger sorting systems this might be a significant component. It would, therefore, be advantageous to get basic data about this.

3. In this study no distinction was made between red and white crawfish as samples were mixtures of the two. Because of expected disparities in basic body dimensions it would be of interest to determine sorting characteristics of the two.

4. It would be interesting to apply the concept of multibody dynamics in modelling the particle behavior of crawfish as it passes through the sorting machine. Probably this is the best method for mathematical modelling because of the propensity of crawfish to clump together in groups of 3 to as much as 5 or 6. This, however, requires high speed computers and extensive program development. It would then be possible to simulate the effect of several variables at a time and with results which closely agree with field data. Then, as a positive offshoot it might be possible to raise the efficiency of sorting machines to new levels.

5. A useful complement to multibody dynamics would be prediction of the kinematic behavior of crawfish using screw theory in which crawfish are treated singly and not in clumps. A combination of the two methods would then provide a frame of reference for crosschecking results, pegging the inherent variability of the data within known limits.

6. It would be of interest to conduct sorting tests on the following:
a) comparison of sorting pond-fresh, live crawfish vs. crawfish which were stored in coolers or refrigerators -- crawfish become more active at higher temperatures, forming clumps which is detrimental to effective sorting. At low temperatures the opposite is true: crawfish become more passive thus permitting smoother flow during the sorting process. It is believed that differences in sorting between these two temperature regimes would not be pronounced unless the low temperature could be maintained during the sorting process. But hard data may prove the contrary.

b) comparison of sorting crawfish with and without flow-through water -- the additional cost of pumping water may be more than offset by the greater value of cleaner crawfish and perhaps more efficient sorting. Whether water flow undermines effective sorting because of a decrease in contact friction has not so far been investigated. Perhaps a decrease in friction would be compensated by a reduction in clumping among crawfish as water flow mimics their natural habitat.

c) handsorting crawfish by trained personnel -- No basic data exists about handsorting crawfish. For example, under the most favorable work environment what is the range of output from hand sorting? And how accurate is human judgment in sorting crawfish according to a predetermined grade standard? Is it possible to write this into mathematical equations? Crawfish for export (jumbo size) are invariably hand sorted because the market costs justify it and human judgment is a safer bet than
a machine sorter. How far can we stretch the validity of this statement?

d) in-boat sorting using a pair of cylindrical rollers -- this presents interesting possibilities especially to the crawfish farmer who is interested in rapid disposal of his crawfish. With an in-boat sorter a crawfish farmer is ready to sell his harvest as soon as he docks his boat. The primary factors to consider are: space and weight constraints, the effect of swaying of the boat, and the necessity of introducing more automation in the control systems. One thing would seem to favor this method which is that it is easy to attach a flow-through water assist system to the sorter if it is proven to be beneficial.
LITERATURE CITED


APPENDIX

APPENDIX A. Fortran 77 Programs

1. PROGRAM BIOPHYS
   COMPUTES HOPPER DIMENSIONS (CYLINDRICAL ROLLER SORTER AND DIVERGING VANE BELT SORTER) FOR NO PARTICLE ARCHING OR BRIDGING (CONSIDERS NORMAL AND TANGENTIAL STRESSES), COMPARES X-SECT. AREA OF ROLLER & BELT SORTER AND ANALYZES VANE BELT INCLUDED ANGLE GEOMETRY.

2. PROGRAM CFSTAT
   REGRESSION OF CRAWFISH BODY WEIGHT (G) WITH RESPECT TO LENGTH (MM) BASED ON ROMAIRE'S EQUATION; COMPUTES SAMPLE STATISTICS (SD, CV, RANGE, INTERVALS, FREQUENCY DISTRIBUTION) FOR ACTUAL SORTER GRADES AND FOR LOUISIANA VOLUNTARY STANDARDS; Sorts CF BODYWEIGHT (G) DATA IN DESCENDING ORDER.

3. PROGRAM DIMCRS
   DETERMINES THE FULL ARRAY OF MATRIX COMBINATIONS (165) WHICH ARISES FROM THE SET OF AUXILIARY EQUATIONS (3x11) OF THE DIMENSIONAL ANALYSIS OF A CYLINDRICAL ROLLER SORTER FOR CRAWFISH; NON-SINGULAR MATRICES ARE IDENTIFIED BY CALCULATING THEIR RESPECTIVE DETERMINANTS USING CRAMER'S CO-FACTOR EXPANSION METHOD.

4. PROGRAM DIMCRS1
   SETS UP MATRIX COMPUTATIONS FOR THE AUXILIARY EQUATIONS IN THE DIMENSIONAL ANALYSIS OF A CYLINDRICAL ROLLER SORTER FOR CRAWFISH; BEGINS WITH FULL ARRAY OF FEASIBLE COMBINATIONS (NON-SINGULAR MATRICES) AND PERFORMS SEQUENTIAL ASSIGNMENT OF VALUE EQUAL TO ONE TO ARBITRARILY CHOSEN DIMENSIONS WITH THE OBJECT OF DETERMINING CORRESPONDING EXPONENTS OF THE VARIOUS DIMENSIONAL GROUPS.

5. PROGRAM DIMVBS
   DETERMINES THE FULL ARRAY OF MATRIX COMBINATIONS (108) WHICH ARISES FROM THE AUXILIARY EQUATIONS (3x9) OF THE DIMENSIONAL ANALYSIS OF A DIVERGING VANE BELT SORTER FOR CRAWFISH; NON-SINGULAR MATRICES ARE
IDENTIFIED BY CALCULATING THEIR RESPECTIVE DETERMINANTS USING THE CO-FACTOR METHOD OF EXPANSION.

6. PROGRAM **DIMVBS1**
   SETS UP MATRIX COMBINATIONS FOR THE AUXILIARY EQUATIONS IN THE DIMENSIONAL ANALYSIS OF A DIVERGING VANE BELT SORTER FOR CRAWFISH; BEGINS WITH FULL ARRAY OF FEASIBLE COMBINATIONS (NON-SINGULAR MATRICES) AND PERFORMS SEQUENTIAL ASSIGNMENT OF VALUE EQUAL TO ONE TO ARBITRARILY CHOSEN DIMENSIONS WITH THE OBJECT OF DETERMINING CORRESPONDING EXPONENTS OF THE VARIOUS DIMENSIONAL GROUPS.

7. PROGRAM **GSSVIB**
   MODELS THE GRID SHAKER SORTER USING A 2-DF SPRING-MASS -DAMPER SYSTEM; CALCULATES AMPLITUDES $X_1$ AND $X_2$ FOR VARIOUS MASS RATIOS.

8. PROGRAM **IYCRS1L**
   COMPUTES SEPARABILITY COEF LAMBDA $\lambda$, CONSIDERING INTRA-CLASS COMPARISONS FOR A 15x4 MATRIX; COLUMNS (4) REPRESENT SIZE GROUPS OF PEELER, MEDIUM, LARGE, AND JUMBO WHILE ROWS (15) REPRESENT SAMPLE REPS.

9. PROGRAM **IYGSS3**
   COMPUTES COEF. OF SEPARABILITY LAMBDA $\lambda$ BY MEANS OF COLUMNWISE SORTING OF 28x2 MATRIX WEIGHT DATA ON GSS AND CORRECTING FOR INTRACLASS REPETITION OF VALUES.

10. PROGRAM **IYVBS5**
    COMPUTES SEPARABILITY COEF LAMBDA $\lambda$, CONSIDERING INTRA-CLASS COMPARISONS FOR A 15x4 MATRIX; COLUMNS (4) REPRESENT SIZE GROUPS OF PEELER, MEDIUM, AND LARGE WHILE ROWS (15) REPRESENT SAMPLE REPS.

11. PROGRAM **MACHDES**
    CALCULATES POWER RANGE FOR VANE BELT SORTER; FORCES ACTING ON A CYLINDRICAL ROLLER SORTER (TREATED AS A SCREW); APPLYING THE CALCULUS MINIMA TO DETERMINE THE LEAST CYLINDRICAL ROLLER SORTER DIAMETER WHICH IS ABLE TO COUNTERBALANCE CRUSHING FORCES; AND, CALCULATES THE PARTICLE STRESS FIELD EXERTED ACROSS THE V-SECTION OF A VANE BELT SORTER BY MEANS OF FLOW EQUATIONS DEVELOPED
FOR GRANULAR MATERIALS; CHARACTERIZE DISPLACEMENT, LINEAR AND ANGULAR VELOCITY AS WELL AS LINEAR AND ANGULAR ACCELERATION OF A POINT ON THE SCREW PATH FOLLOWED BY THE CYLINDRICAL ROLLER SORTER OVER THE EXPERIMENTAL RANGE OF SORTING RPM (20 TO 30 RPM).

12. PROGRAM **OPDPEL**

C PROGRAM **BIOPHYS**

REAL AREAR,AREAB,DR,CLEAR,LB,THETA1,RATIO

REAL SN,SS,SX,SY,THETA2,R,C,RATIO,
+ SIGMAC,W,B,SINTHET2,THETA2IF

PARAMETER(SX=19,SY=25.,W=25)

REAL THETA3,ALPHA

INTEGER I,J

PARAMETER(DR=6.625,CLEAR=0.47165,LB=6.00,PI=3.14159)

AREAR=(DR**2)*(1-PI/4)+(DR/2)*CLEAR

THETA=0.0

PRINT*," THE AREAR AREAB RATIO"

DO 10 1=1,150

THETA1=THETA1+1

AREAB=(LB**2)/2*(SIND(THETA1)) +
+ LB*(COSD(THETA1/2))*CLEAR

RATIO=AREAR/AREAB

PRINT 9,THETA1,AREAR,AREAB,RATIO

9 FORMAT(F5.1,1X,3(F7.4,1X))

10 CONTINUE

THETA2=1.

PRINT*," THE SN SS RATIO S2THE2"

DO 20 I=1,45

R=(SY-SX)/2
C=(SY+SX)/2
SN=R+C*COSD(2*THETA2)
SS=R*SIND(2*THETA2)
RATIO=SN/SS
IF(SS.NE.0.0)THEN
PRINT 19,THETA2,SN,SS,RATIO,SIND(2*THETA2)
19 FORMAT(F5.1,1X,4(F7.4,1X))
END IF
THETA2=THETA2+1
20 CONTINUE

PRINT*,R,C
SIGMAC=2*R
B=SIGMAC/W
SINTHET2=(SY-SX)/(SY+SX)
THETA2IF=ASIND(SINTHET2)
PRINT *,B,THETA2IF

C PROGRAM FOR BELT INC ANGL GEOM
THETA3=5.0
PRINT*,' THE3 ALP C D'
DO 40 I=1,71
   C=0.445
   DO 30 J=1,32
      D=2*6*SIND(THETA3)+C
      PRINT 29,THETA3,ALPHA,C,D
   29 FORMAT(F4.1,1X,3(F8.4,1X))
      C=C+0.03125
   30 CONTINUE
THETA3=THETA3+1
ALPHA=2*THETA3
40 CONTINUE
END
C END OF BIOPHYS

C PROGRAM CFSTAT
INTRINSIC LOG10
REAL X(552),CBL(552),SUMCBL,AVECBL,CBLSS,CBLSD,CBLCV

REAL XX(110),Y(110),YL,YC,YCL,DS,SUMDS,SDYXX,RSQ,R
INTEGER I,J,K,FREQVC1,FREQVC2,FREQVC3,FREQVC4,
+ FREQC1,FREQC2,FREQC3,FREQC4
PARAMETER(B=2.17898,C=-3.31077,SDY=0.13716)
OPEN(25,FILE='cclwd4',STATUS='OLD')
SUMDS=0.0
PRINT 60
60  FORMAT(/T10,' CFL',8X,' W',8X,' W(P)'/)

DO 20 I=1,110
   READ(25,*END=21) XX(I),Y(I)
   YL=LOG10(Y(I))
   YCL=C+B*LOG10(XX(I))
   YC=10**YCL
   DS=(YL-YCL)**2
   SUMDS=SUMDS+DS
   PRINT*,XX(I),Y(I),YC
   IF(I.EQ.110)THEN
      SDYXX=SQRT(SUMDS/108.)
      RSQ=(1-(SDYXX/SDY)**2)
      R=SQRT(RSQ)
      PRINT 9, SDYXX,SDY,RSQ,R
      9  FORMAT(/T16,'SDYXX ='1X,F8.6/T16,' SDY =',1X,F8.6/ +
         T16,'RSQ =',1X,F8.6/T16,'R =',1X,F8.6/)
   ELSE
      GO TO 20
   END IF
20  CONTINUE
21  CLOSE(25)

OPEN(70,FILE='st4o',STATUS='OLD')

PRINT *, ' N WEIGHT LENGTH'
SUMCBL=0.0
CBLSS=0.0
I=1

FREQVC1=0
FREQVC2=0
FREQVC3=0
FREQVC4=0
FREQC1=0
FREQC2=0
FREQC3=0
FREQC4=0
DO 10 J=1,552
READ(70,*,END=15) X(J)

IF(X(J).GE.29.3)THEN
  FREQVC1=FREQVC1+1
ELSE IF(X(J).GE.22.2.AND.X(J).LE.29.2)THEN
  FREQVC2=FREQVC2+1
ELSE IF(X(J).GE.17.8.AND.X(J).LE.22.1)THEN
  FREQVC3=FREQVC3+1
ELSE IF(X(J).LE.17.7)THEN
  FREQVC4=FREQVC4+1
END IF

CBL(J)=10**((LOG10(X(J))+5.0537)/3.277)

IF(CBL(J).LE.133.1.AND.CBL(J).GE.117.6)THEN
  FREQC1=FREQC1+1
ELSE IF(CBL(J).LE.117.5.AND.CBL(J).GE.102.1)THEN
  FREQC2=FREQC2+1
ELSE IF(CBL(J).LE.102.0.AND.CBL(J).GE.86.7)THEN
  FREQC3=FREQC3+1
ELSE IF(CBL(J).LE.86.6.AND.CBL(J).GE.71.2)THEN
  FREQC4=FREQC4+1
END IF

SUMCBL=SUMCBL+CBL(J)
CBLSS=CBLSS+(CBL(J))**2
PRINT 6, J,X(J),CBL(J)
6 FORMAT(T8,I3,2(F7.1))

IF(I.EQ.1)THEN
  CBLMAX=CBL(J)
  CBLMIN=CBL(J)
END IF

I=0
IF(J.GT.1)THEN
  GO TO 7
END IF

7 IF(CBLMAX.LT.CBL(J))THEN
  CBLMAX=CBL(J)
END IF
IF(CBLMIN.GT.CBL(J)) THEN
CBLMIN=CBL(J)
END IF

IF(J.EQ.552) THEN
AVECBL=SUMCBL/552.
CBLSD=SQRT((CBLSS-(SUMCBL**2.)/552.)/(552.-1))
CBLCV=(CBLSD/AVECBL)*100.
PRINT 8, SUMCBL, AVECBL, CBLSD, CBLCV, CBLMAX,
+ CBLMIN, FREQC1, FREQC2, FREQC3, FREQC4, FREQVC1,
+ FREQVC2, FREQVC3, FREQVC4
8 FORMAT(//T8, 'GRAND TOTAL=', 1X, F7.1/T8,
+ 'GRAND MEAN =', 3X, F5.1/T8, 'CBLSD =', 8X, F5.1/
+ T8, 'CBLCV =', 8X, F5.1/T8, 'CBLMAX =', 7X, F5.1/
+ T8, 'CBLMIN =', 7X, F5.1/T8, 'FREQC1 =', 7X, I3/
+ T8, 'FREQC2 =', 7X, I3/T8, 'FREQC3 =', 7X, I3/T8
+ , 'FREQC4 =', 7X, I3/T8, 'FREQVC1 =', 6X, I3/T8,
+ 'FREQVC2 =', 6X, I3/T8, 'FREQVC3 =', 6X, I3/T8,
+ 'FREQVC4 =', 6X, I3)
ELSE
GO TO 10
END IF

10 CONTINUE

15 CLOSE(70)

RANGE=CBLMAX-CBLMIN
H=RANGE/4
PRINT 16, RANGE, H
16 FORMAT(//T8, 'RANGE=', 10X, F4.1/T8, 'INTERVAL=', 7X, F4.1)
PRINT 17
17 FORMAT(//T8, 'CLASS', 1X, 'LOWER CI', 1X, 'UPPER CI')
CILL=CBLMAX

DO 25 K=1, 4
  CILL=CILL-H
  CIUL=CILL+H
  IF(K.EQ.1) THEN
    CILL=CILL+0.10
  ELSE
    CIUL=CIUL-0.10
  END IF
25 CONTINUE
END IF

PRINT 19, K,CILL,CIUL
19 FORMAT(T8,I3,1X,F8.1,1X,F8.1)
25 CONTINUE

READ(70,*,END=1)(X(J),J=1,552)
1 CALL SORT(X,552)
PRINT*, 'CF WT(G) SORTED IN DESCENDING ORDER'
PRINT 26,X
26 FORMAT(F5.2)
END

SUBROUTINE SORT(X,N)
REAL X(N)
EXCHNG=1
5 IF(EXCHNG.EQ.1)THEN
EXCHNG=0
DO 10 I=1,N-1
   IF(X(I).LT.X(I+1))THEN
      TEMP=X(I)
      X(I)=X(I+1)
      X(I+1)=TEMP
      EXCHNG=1
   END IF
10 CONTINUE
GO TO 5
END IF
RETURN
END

END OF CFSTAT

C PROGRAM DIMCRS

C VARIABLES:
C X(1:3,1:9) = COEFFICIENTS OF THE AUXILIARY
C EQUATIONS.
C Y(4095) = INDEX FOR LISTING UNIQUE
C COMBINATORIAL SUBSCRIPTS GENERATED
C BY SUBROUTINE 'SCAN' IN
C CONJUNCTION WITH SUBROUTINE 'CODE'.
C Z11,Z21,...,Z33 = ELEMENTS OF A 3X3 MATRIX
C TRANSFERRED TO SUBROUTINE 'DETERM'.
REAL X(1:3,1:11),Y(495),Z11,Z21,Z31,Z12,Z22,Z32,
  Z13,Z23,Z33
INTEGER I,J,NCOM(1:495,1:3),K1,K2,K3

OPEN(650,FILE='dimdatc',STATUS='OLD')
READ(650,*,END=21)((X(I,J),J=1,11),I=1,3)
OPEN(92,FILE='pkijc',STATUS='OLD')
READ(92,*,END=22) (Y(I),I=1,495)
OPEN(97,FILE='matcrs',STATUS='OLD')
READ(97,1,END=23)((NCOM(I,J),J=1,3),I=1,495)

1 FORMAT(I2,1X,I2,1X,I2)
PRINT*,'The auxiliary equation in matrix form is:'
PRINT 2,X
2 FORMAT(11(F4.1,1X))
DO 10 I=1,495,3
  DO 9 J=1,3
    K1=NCOM(I,J)
    K2=NCOM(I,J+1)
    K3=NCOM(I,J+2)
    Z11=X(1,K1)
    Z21=X(2,K1)
    Z31=X(3,K1)
    Z12=X(1,K2)
    Z22=X(2,K2)
    Z32=X(3,K2)
    Z13=X(1,K3)
    Z23=X(2,K3)
    Z33=X(3,K3)
    IF(J.EQ.1)THEN
      PRINT 3
    END IF
  CONTINUE
3 FORMAT('/15X,'K1',1X,'K2',1X,'K3',3X,'Z11',2X,'Z12',2X,'Z13',13',
            '2X,Z21',2X,'Z22',2X,'Z23',2X,'Z31',2X,'Z32',2X,'Z33')
PRINT 4,K1,K2,K3,Z11,Z12,Z13,Z21,Z22,Z23,Z31,Z32,Z33
  CALL DETERM(Z11,Z21,Z31,Z12,Z22,Z32,Z13,Z23,Z33)
END IF
4 FORMAT(15X,3(I2,1X),9(F4.1,1X))
9 CONTINUE
10 CONTINUE
PRINT*, ''
CALL SCAN
PRINT 13
13 FORMAT(2X,'T',4X,'Y(I)')
DO 15 I=1,495
PRINT 14,I,Y(I)
14 FORMAT(I3,1X,F8.0)
15 CONTINUE
CALL CODE(Y,495)
CALL MATCOM
21 CLOSE(650)
22 CLOSE(92)
23 CLOSE(97)
END

C THIS SUBROUTINE WRITES ALL POSSIBLE SUBSCRIPTS
C WHICH DEFINE COEFFICIENTS OF THE AUXILIARY
C EQUATIONS (9 C COMBINATIONS TAKEN 3 AT A TIME);
C IT STARTS WITH A TRIANGULAR MATRIX, PROGRESSIVELY
C ELIMINATING DUPLICATED SUBSCRIPTS.

SUBROUTINE SCAN
INTEGER I,J,K,NCR
REAL PKIJ,KIJ
NCR=0
PRINT 16
16 FORMAT(1X,'K',2X,T,2X,'J ',5X,'K IJ',5X,'PK IJ')
DO 50 K = 1,11
DO 40 I=1,11
DO 30 J=1,I
   IF(K.NE.I.AND.K.NE.J)THEN
      IF(I.NE.J)THEN
         PKIJ=K**5+I**5+J**5
         KIJ=10000*K+100*I+J
         WRITE(19,*) K,I,J,PKIJ
         WRITE(91,17) PKIJ
      END IF
   ELSE
      END IF
30 CONTINUE
17 FORMAT(F8.0)
PRINT 20,K,I,J,KIJ,PKIJ
20 FORMAT(I2,1X,I2,1X,I2,1X,F8.0,I2,1X,F8.0)
NCR=NCR+1
ELSE
   END IF
   END IF
30 CONTINUE
CONTINUE
CONTINUE
PRINT 51,NCR
FORMAT('The raw total of NCRs = ',i3)
RETURN
END

C THIS SUBROUTINE USES EXCHANGE SORTING TECHNIQUE
C TO WRITE SUBSCRIPT INDICES IN ASCENDING ORDER,
C LISTING THE FREQUENCY OF REPETITION AND
C CALCULATING THE FINAL FEASIBLE SUBSCRIPTS.

SUBROUTINE CODE(X,N)
REAL X(N),TEMP,TEMPO
INTEGER J,K,L,EXCHNG,COUNTSIM
COUNTSIM=0
EXCHNG=1
30 IF(EXCHNG.EQ.1)THEN
EXCHNG=0
DO 10 J=1,N-1
IF(X(J).GT.X(J+1))THEN
TEMP=X(J)
X(J)=X(J+1)
X(J+1)=TEMP
EXCHNG=1
END IF
10 CONTINUE
GO TO 30
END IF

PRINT 18
18 FORMAT(/2X,' N',5X,' Y(I)',2X,' FREQ')
DO 20 K=1,N
IF(X(K).EQ.X(K+1))THEN
COUNTSIM=COUNTSIM+1
TEMPO=X(K+1)
X(K)=TEMPO
END IF
PRINT 19,K,X(K),COUNTSIM
19 FORMAT(I3,1X,F8.0,2X,I3)
20 CONTINUE

DO 50 L=1,N,3
WRITE(93,49)X(L)
SUBROUTINE MATCOM
INTEGER I,L
REAL X(165),Y(495),Z(495),W(495),U(495),DIFF
OPEN(94,FILE='pkij1',STATUS='OLD')
READ(94,*,END=31)(X(L),L=1,165)
OPEN(95,FILE='kijp',STATUS='OLD')
READ(95,*,END=32)(Y(I),Z(I),W(I),U(I),I=1,495)
PRINT 1
1 FORMAT(/2X,' L',1X,' Y(I)',1X,' Z(I)',1X,' W(I)')
DO 150 L=1,165
   DO 100 I=1,495
      DIFF=X(L)-U(I)
      IF(DIFF.EQ.0.0)THEN
         WRITE(96,*)Y(I),Z(I),W(I)
         PRINT 2,L,Y(I),Z(I),W(I)
      END IF
   100 CONTINUE
150 CONTINUE
31 CLOSE(94)
32 CLOSE(95)
RETURN
END

C THIS SUBROUTINE COMPARES SUBSCRIPT INDICES AND
C DELETES REPEATED COMBINATIONS BY MEANS
C OF A DOUBLE INTERNAL LOOP.

REAL A(1:3,1:3),W11,W21,W31,W12,W22,W32,W13,W23,W33,
+ ELEM1,ELEM2,ELEM3,DET
INTEGER I,J
A(1,1)=W11
A(1,2)=W21
A(1,3)=W31
A(2,1)=W12
A(2,2)=W22
A(2,3)=W32
A(3,1)=W13
A(3,2)=W23
A(3,3)=W33
PRINT*, 'The 3x3 matrix is:'
PRINT 4, A
4 FORMAT(3(F4.1,1X))
DO 20 J = 1, 1
DO 10 I = 1, 3
IF (I.EQ.1) THEN
  ELEM 1 = (-1)**(I+J)*A(I,J)*A(I+1,J+1)*A(I+2,J+2)
  + A(I+2,J+1)*A(I+1,J+2))
ELSEIF (I.EQ.2) THEN
  ELEM 2 = (-1)**(I+J)*A(I,J)*A(I-1,J+1)*A(I+1,J+2)
  + A(I-1,J+1)*A(I+1,J+2))
ELSEIF (I.EQ.3) THEN
  ELEM 3 = (-1)**(I+J)*A(I,J)*A(I-2,J+1)*A(I-1,J+2)
  + A(I-1,J+1)*A(I-2,J+2))
ELSE
  END IF
  DET = ELEM 1 + ELEM 2 + ELEM 3
10 CONTINUE
PRINT 5, DET
5 FORMAT(/ The determinant is = ', 1X, F4.0)
20 CONTINUE
RETURN
END

C END OF DIMCRS

C PROGRAM DIMCRS1
INTEGER I,J,K,L,M(1:165,1:3),N(1:495,1:3),TEMPO,NN(1:165,1:11),
  INDEX
REAL X(1:3,1:11)
OPEN(85, FILE='dimdatc', STATUS='OLD')
READ(85,5,END=11)((X(I,J),J=1,11),I=1,3)
5 FORMAT(11(F3.0,1X))
OPEN(86, FILE='matcrs', STATUS='OLD')
READ(86,6,END=12)((N(K,L),L=1,3),K=1,495)
READ(61, END=160)(NN(K',T'), T', 11, K'=1,165)
OPEN(61, STATUS=OLD)
CONTINUE
80
70
61
FORMAT(13, 1'2', 1'2', T', I'2', 1'2', I'2')
PRINT 61. K', NN(K', T'),
WRITE(61, *) NN(K', T')
END IF
NN(K', T')=L
ELSE IF(NN(K', T')) THEN
DO 70 L=1, 11
DO 80 K=1, 165
CONTINUE
60
60
50
50
49
FORMAT(13, 1'2', I'2', I'2')
PRINT 49. K', NN(K', T')
END IF
M(K', T')=0.0
IRL=3. THEN
DO 60 L=1, 11
DO 60 K=1, 165
CONTINUE
40
40
30
30
Print 121',
FORMAT(3, I'2', I'2', I'2')
WRITE(25, 121', N)
END IF
CALL SORT(N', 3)
IRL=EG. THEN
DO 30 L=1, 13
DO 40 K=1, 1
CONTINUE
20
20
19
19
PRINT 19. K', 1')
DO 10 J=1, 11
DO 20 J=1, 13
(READ(60, END=13)(M(K', T')=1.3, K'=1,165)
OPEN(60, FILE=mer Lit, STATUS=OLD)
FORMAT(3, 2', 1'2')
)
DO 110 K=1,165
INDEX=1
DO 100 I=1,11
DO 90 L=1,11
   IF(INDEX.EQ.L)THEN
      MM=1
   ELSE
      MM=0
   END IF
   IF(NN(K,L).GT.0.0)THEN
      MM=NN(K,L)
   END IF
   PRINT*,K,I,L,MM
90 CONTINUE
INDEX=INDEX+1
PRINT*,'  '
100 CONTINUE
110 CONTINUE
11 CLOSE(85)
12 CLOSE(86)
13 CLOSE(60)
END

SUBROUTINE SORT(X,N)
INTEGER X(N)
EXCHNG=1
27 IF(EXCHNG.EQ.1)THEN
   EXCHNG=0
   DO 30 K=1,N-1
      IF(X(K).LT.X(K+1))THEN
         TEMP=X(K)
         X(K)=X(K+1)
         X(K+1)=TEMP
         EXCHNG=1
      END IF
30 CONTINUE
GO TO 27
END IF
RETURN
END

C END OF DIMCRS1
C PROGRAM DIMVBS
C VARIABLES:
C X(1:3,1:9) = COEFFICIENTS OF THE AUXILIARY EQUATIONS.
C Y(252) = INDEX FOR LISTING UNIQUE
C COMBINATORIAL
C SUBSCRIPTS GENERATED BY SUBROUTINE
C SCAN' IN CONJUNCTION WITH
C 'CODE'.
C Z11,Z21,..,Z33 = ELEMENTS OF A 3X3 MATRIX
C TRANSFERRED TO SUBROUTINE 'DETERM'.
C NCOM(1:252,1:3) = ARRAY OF COMBINATORIAL SUBSCRIPTS
C USED TO DEFINE ELEMENTS OF 3X3 MATRIX,
C GENERATED BY SUBROUTINE 'MATCOM'.

REAL X(1:3,1:9),Y(252),Z11,Z21,Z31,Z12,Z22,Z32,
+ Z13,Z23,Z33
INTEGER I,J,NCOM(1:252,1:3),K1,K2,K3

OPEN(651,FILE='dimdatv',STATUS='OLD')
READ(651,*,END=21)((X(I,J),J=1,9),I=1,3)
OPEN(93,FILE='pkijv',STATUS='OLD')
READ(93,*,END=22) (Y(I),I=1,252)
OPEN(98,FILE='matvbs',STATUS='OLD')
READ(98,1,END=23)((NCOM(I,J),J=1,3),I=1,252)

1 FORMAT(I2,1X,I2,1X,I2)
PRINT*, 'The auxiliary equation in matrix form is:'
WRITE(*,2)((X(I,J),J=1,9),I=1,3)

2 FORMAT(9(F4.1,1X))

DO 10 I=1,252,3
   DO 9 J=1,3
      K1=NCOM(I,J)
      K2=NCOM(I,J+1)
      K3=NCOM(I,J+2)
      Z11=X(1,K1)
      Z21=X(2,K1)
      Z31=X(3,K1)
      Z12=X(1,K2)
      Z22=X(2,K2)
      Z32=X(3,K2)
      Z13=X(1,K3)
      Z23=X(2,K3)
      Z33=X(3,K3)

10 CONTINUE
IF(J.EQ.1)THEN
PRINT 3
3 FORMAT(/15X,'K1',1X,'K2',1X,'K3',3X,'Z11',2X,'Z12',2X,'Z13',
2X,'Z21',2X,'Z22',2X,'Z23',2X,'Z31',2X,'Z32',2X,'Z33')
PRINT 4,K1,K2,K3,Z11,Z12,Z13,Z21,Z22,Z23,Z31,Z32,Z33
CALL DETERM(Z11,Z21,Z31,Z12,Z22,Z32,Z13,Z23,Z33)
END IF
4 FORMAT(15X,3(I2,1X),1X,9(F4.1,1X)/)
9 CONTINUE
10 CONTINUE
PRINT*,''
CALL SCAN
13 FORMAT(2X,T,4X,'Y(I)')
DO 15 I=1,252
PRINT 14,I,Y(I)
14 FORMAT(I3,1X,F8.0)
15 CONTINUE
CALL CODE(Y,252)
CALL MATCOM
21 CLOSE(651)
22 CLOSE(93)
23 CLOSE(98)
END

C THIS SUBROUTINE WRITES ALL THE POSSIBLE SUBSCRIPTS
C WHICH DEFINE COEFFICIENTS OF THE AUXILIARY
C EQUATIONS (9 COMBINATIONS TAKEN 3 AT A TIME);
C IT STARTS WITH A TRIANGULAR MATRIX, PROGRESSIVELY
C ELIMINATING DUPLICATED SUBSCRIPTS.

SUBROUTINE SCAN
INTEGER I,J,K,NCR
REAL PKIJ,KIJ
NCR=0
PRINT 16
16 FORMAT(1X,'K',2X,'T',2X,'J',5X,'KIJ',5X,'PKIJ')
DO 50 K=1,9
DO 40 I=1,9
DO 30 J=1,I
IF(K.NE.I.AND.K.NE.J)THEN
IF(I.NE.J)THEN
PKIJ=K**5+I**5+J**5
KIJ=10000*K+100*I+J
ENDIF
ENDIF
50 CONTINUE
40 CONTINUE
30 CONTINUE
END
WRITE(20,*) K,I,J,PKIJ
WRITE(92,17) PKIJ
17 FORMAT(F8.0)
PRINT 20,K,I,J,KIJ,PKIJ
20 FORMAT(I2,1X,I2,1X,I2,1X,F8.0,1X,F8.0)
NCR=NCR+1
ELSE
END IF
END IF
30 CONTINUE
40 CONTINUE
50 CONTINUE
PRINT 51,NCR
51 FORMAT(/The raw total of NCRs = ',13/
RETURN
END

C THIS SUBROUTINE USES EXCHANGE SORTING TO WRITE
C SUBSCRIPT INDICES IN ASCENDING ORDER, LISTING THE
C FREQUENCY OF REPETITION, AND CALCULATING THE FINAL
C FEASIBLE SUBSCRIPTS.

SUBROUTINE CODE(X,N)
REAL X(N),TEMP,TEMPO
INTEGER J,K,L,EXCHNG,COUNTSIM
COUNTSIM=0
EXCHNG=1
30 IF(EXCHNG.EQ.1)THEN
EXCHNG=0
DO 10 J=1,N-1
   IF(X(J).GT.X(J+1))THEN
      TEMP=X(J)
      X(J)=X(J+1)
      X(J+1)=TEMP
      EXCHNG=1
   END IF
10 CONTINUE
GO TO 30
END IF

PRINT 18
18 FORMAT(/2X,' N',5X,' Y(I)',2X,' FREQ')
DO 20 K=1,N
IF(X(K).EQ.X(K+1))THEN
COUNTSIM=COUNTSIM+1
TEMPO=X(K+1)
X(K)=TEMPO
END IF
PRINT 19,K,X(K),COUNTSIM
19 FORMAT(I3,1X,F8.0,2X,I3)
20 CONTINUE

PRINT 48
48 FORMAT(/4X,'X(L)')
DO 50 L=1,N,3
WRITE(94,49)X(L)
PRINT 49,X(L)
49 FORMAT(F8.0)
50 CONTINUE
RETURN

C THIS SUBROUTINE COMPARES SUBSCRIPT INDICES AND
C DELETES REPEATED COMBINATIONS BY MEANS OF
C A DOUBLE INTERNAL LOOP.

SUBROUTINE MATCOM
INTEGER I,L
REAL X(84),Y(252),Z(252),W(252),U(252),DIFF
OPEN(95,FILE='pkijs',STATUS='OLD')
READ(95,*,END=31)(X(L),L=1,84)
OPEN(96,FILE='pkijsc',STATUS='OLD')
READ(96,*,END=32)(Y(I),Z(I),W(I),U(I),I=1,252)
PRINT 1
1 FORMAT(/2X,L',1X,Y(I),1X,Z(I)',1X,W(I)')
DO 150 L=1,84
   DO 100 I=1,252
      DIFF=X(L)-U(I)
      IF(DIFF.EQ.0.0)THEN
         WRITE(97,*)Y(I),Z(I),W(I)
         PRINT 2,L,Y(I),Z(I),W(I)
      END IF
   100 CONTINUE
150 CONTINUE
31 CLOSE(95)
32 CLOSE(96)
RETURN
END
C THIS SUBROUTINE USES THE CO-FACTOR METHOD TO
C CALCULATE THE DETERMINANT OF A 3X3 MATRIX OBTAINED
C FROM VARIOUS FEASIBLE COMBINATIONS IN THE MAIN
C PROGRAM.

SUBROUTINE DETERM(W11,W21,W31,W12,W22,
+ W32,W13,W23,W33,
REAL A(1:3,1:3),W11,W21,W31,W12,W22,W32,W13,W23,W33,
+ ELEM1,ELEM2,ELEM3,DET
INTEGER I,J
A(1,1)=W11
A(1,2)=W21
A(1,3)=W31
A(2,1)=W12
A(2,2)=W22
A(2,3)=W32
A(3,1)=W13
A(3,2)=W23
A(3,3)=W33
PRINT*, 'The 3x3 matrix is:
PRINT 4,A
4 FORMAT(3(F4.1,1X))
DO 20 J=1,3
DO 10 I=1,3
IF(I.EQ.1)THEN
ELEM1=((-1)**(I+J))*A(I,J)**(A(I+1,J+1)*A(I+2,J+2)
+ -A(I+2,J+1)*A(I+1,J+2))
ELSEIF(I.EQ.2)THEN
ELEM2=((-1)**(I+J))*A(I,J)**(A(I-1,J+1)*A(I+1,J+2)
+ -A(I+1,J+1)*A(I-1,J+2))
ELSEIF(I.EQ.3)THEN
ELEM3=((-1)**(I+J))*A(I,J)**(A(I-2,J+1)*A(I-1,J+2)
+ -A(I-1,J+1)*A(I-2,J+2))
ELSE
DET=ELEM1+ELEM2+ELEM3
END IF
PRINT 5,DET
5 FORMAT(/'The determinant is = ',1X,F4.0)
20 CONTINUE
RETURN
END
C END OF DIMVBS

C PROGRAM DIMVBS1
INTEGER I,J,K,L,N(1:252,1:3),TEMPO,NN(1:84,1:11),
+ M(1:84,1:3),INDEX,MM
REAL X(1:3,1:11)

OPEN(75,FILE='dimdatv',STATUS='OLD')
READ(75,5,END=11)((X(I,J),J=1,11),I=1,3)
OPEN(76,FILE='matvbs',STATUS='OLD')
READ(76,6,END=12)((N(K,L),L=1,3),K=1,252)
5 FORMAT(11(F3.0,1X))
6 FORMAT(3(I2,1X))
OPEN(40,FILE='matvbst',STATUS='OLD')
READ(40,121,END=13)((M(K,L),L=1,3),K=1,84)
OPEN(41,STATUS='OLD')
READ(41,*,END=160)((NN(K,L),L=1,11),K=1,84)

DO 10 I=1,3
DO 20 J=1,11
PRINT 19,X(I,J)
19 FORMAT(11(F3.0,1X))
20 CONTINUE
10 CONTINUE

DO 130 K=1,1
DO 120 L=1,3
IF(L.EQ.3)THEN
CALL SORT(N,3)
END IF
PRINT 121,N
WRITE(39,121)N
121 FORMAT(3(I2,1X))
120 CONTINUE
130 CONTINUE

DO 150 K=1,84
DO 140 L=1,11
IF(L.GT.3)THEN
M(K,L)=0.0
END IF
WRITE(40,*)M(K,L)
PRINT 40,K,L,M(K,L)
40 FORMAT(I2,1X,I2,1X,I2)
CONTINUE
CONTINUE

DO 151 K=1,84
DO 141 L=1,11
   IF(L.EQ.M(K,L)) THEN
      NN(K,L)=L
   ELSE
      TEMPO=M(K,L)
      NN(K,TEMPO)=TEMPO
   END IF
   WRITE(41,:|:)NN(K,L)
   PRINT 41,K,L,NN(K,L)
   WRITE(41,*)NN(K,L)
   PRINT 41,K,L,NN(K,L)
41 FORMAT(I2,1X,I2,1X,I2,1X,I2)
CONTINUE
141 CONTINUE

CONTINUE
151 CONTINUE

INDEX=1
DO 162 I=1,11
DO 161 L=1,11
   IF(INDEX.EQ.L) THEN
      MM=1
   ELSE
      MM=0
   END IF
   IF(NN(K,L).GT.0.0) THEN
      MM=NN(K,L)
   END IF
   PRINT*,K,I,L,MM
161 CONTINUE
INDEX=INDEX+1
PRINT*,INDEX
162 CONTINUE
163 CONTINUE

CLOSE(75)
CLOSE(76)
CLOSE(40)
END

SUBROUTINE SORT(X,N)
INTEGER X(N)
EXCHNG=1
IF(EXCHNG.EQ.1)THEN
EXCHNG=0
DO 30 K=1,N-1
     IF(X(K).LT.X(K+1))THEN
         TEMP=X(K)
         X(K)=X(K+1)
         X(K+1)=TEMP
         EXCHNG=1
     END IF
30 CONTINUE
GO TO 27
END IF
RETURN
END

C END OF DIMVBS1

C PROGRAM GSSVIB
REAL X1,X2,PSI,G,F,U,C1,K1,M1,NUMER,DENOM
INTEGER J
PARAMETER(PSI=0.046,G=0.14,F=0.12,C1=7.44,K1=840.,M1=0.16)

PRINT*,'  MASS RATIO AMPL1 AMPL2'
DO 10 J=0,199
     U=J*.05
     GS=G**2
     FS=F**2
     NUMER=(2*PSI*G)**2+(GS-FS)**2
     DENOM=((2*PSI*G)**2)*(GS-1+U*GS+C1*(FS-GS))**2+(U*FS*GS+(GS-1)*(GS-FS)-2*C1*PSI*GS*SQRT(K1/M1))**2
     X1=SQRT(NUMER/DENOM)
     X2=X1*(FS+2*G*PSI)/(FS-GS+2*G*PSI)
8   PRINT 5,U,X1,X2
10 CONTINUE
PRINT 50,PSI,G,F,U,C1,K1,M1,X1,X2

50 FORMAT(//T16,' PSI= ',2X,F5.3//T16,'  G = ',2X,F4.2//T16,'  F = ',2X,F4.2//T16,'  U = ',2X,F3.1//T16,'C1 = ',2X,F4.2//T16,' K1 =',F6.2//T16,' M1 = ',2X,F4.2//T21,' X1 = ',1X,
C END OF GSSVIB

C PROGRAM IYCRS1L

DIMENSION X(60),Y(60),Z(60),ZP(15),ZM(15),ZL(15),ZJ(15)
REAL X(1:15,1:4),Y(1:60),Z(1:60),DIFF,COUNTP,COUNTM,
+ COUNTL,COUNTJ,LAMBDAP,LAMBDAM,LAMBDAL,LAMBDAJ
INTEGER I,J,K,L,M

COUNTP=-23.
COUNTM=-21.
COUNTL=-19.
COUNTJ=-21.
F=15.

OPEN(190,FILE='crs1l',STATUS='OLD')
OPEN(191,FILE='crs1l',STATUS='OLD')
OPEN(192,FILE='crs1lcor',STATUS='OLD')

DO 50 J=1,4
DO 50 I=1,15
READ(190,90,END=21)X
90 FORMAT(F4.1,1X,F4.1,1X,F5.1,1X,F5.1)
PRINT 1,X
1 FORMAT(//7X,'Peeler',5X,'Medium',7X,'Large',6X,'Jumbo'/)
PRINT 3,Y
PRINT 4
DO 40 L=1,60

DO 50 K=1,60
READ(191,91,END=22)Y
91 FORMAT(F4.1,1X,F4.1,1X,F5.1,1X,F5.1)
PRINT 2
2 FORMAT(//7X,'Peeler',5X,'Medium',7X,'Large',6X,'Jumbo'/)
PRINT 3,Y
3 FORMAT(4(7X,F5.1,1X))
PRINT 4
4 FORMAT(//3X,'L',2X,'M',3X,'Z',4X,'Y',3X,'DIFF',3X,'CP',3X,'CM',3X,'CL',3X,'CJ',5X,'LP',5X,'LM',
+ 5X,'LL',5X,'LJ'/)

DO 40 L=1,60
READ(192,90,END=23)Z(L)
IF(L.LE.15)THEN
ZP(L)=Z(L)
ELSEIF(L.GE.16.AND.L.LE.30)THEN
ZM(L-15)=Z(L)
ELSEIF(L.GE.31.AND.L.LE.45)THEN
ZL(L-30)=Z(L)
ELSE
IF(L.GE.46.AND.L.LE.60)THEN
ZJ(L-45)=Z(L)
END IF
END IF
END IF
DO 30 M=1,60
DIFF=Z(L)-Y(M)
IF(DIFF.EQ.0.0)THEN
IF(L.GE.1.AND.L.LE.15)THEN
COUNTP=COUNTP+1
LAMBDAP=(1-COUNTP/F)*100
ELSEIF(L.GE.16.AND.L.LE.30)THEN
COUNTM=COUNTM+1
LAMBDAM=(1-COUNTM/F)*100
ELSEIF(L.GE.31.AND.L.LE.45)THEN
COUNTL=COUNTL+1
LAMBDAL=(1-COUNTL/F)*100
ELSEIF(L.GE.46.AND.L.LE.60)THEN
COUNTJ=COUNTJ+1
LAMBDAJ=(1-COUNTJ/F)*100
ELSE
END IF
END IF
PRINT 29,L,M,Z(L),Y(M),DIFF,
+ COUNTP,COUNTM,COUNTL,COUNTJ,
+ LAMBDAP,LAMBDAM,LAMBDAL,LAMBDAJ
F0RMAT(2X,I2,1X,I2,1X,F5.1,1X,F5.1,1X,F5.1,
+ 2X,F4.0,1X,F4.0,1X,F4.0,1X,F4.0,1X,F4.0,2X,
+ F6.2,1X,F6.2,1X,F6.2,1X,F6.2)
IF(M.EQ.60)THEN
IF(L.EQ.15)THEN
CALL SORT(ZP,15)
ELSEIF(L.EQ.30)THEN
CALL SORT(ZM,15)
ELSEIF(L.EQ.45)THEN
CALL SORT(ZL,15)
ELSEIF(L.EQ.60)THEN
CALL SORT(ZJ,15)
ELSE
END IF
END IF
30 CONTINUE
40 CONTINUE
50 CONTINUE
21 CLOSE(190)
22 CLOSE(191)
23 CLOSE(192)
END

SUBROUTINE SORT(X,N)
REAL X(N),TEMP,TEMPO
INTEGER J,K,EXCHNG,COUNTSIM
COUNTSIM=0
EXCHNG=1
30 IF(EXCHNG.EQ.1)THEN
EXCHNG=0
DO 10 J=1,N-1
   IF(X(J).GT.X(J+1))THEN
      TEMP=X(J)
      X(J)=X(J+1)
      X(J+1)=TEMP
      EXCHNG=1
   END IF
10 CONTINUE
GO TO 30
END IF

DO 20 K=1,N
IF(X(K).EQ.X(K+1))THEN
   COUNTSIM=COUNTSIM+1
   TEMPO=X(K+1)
   X(K)=TEMPO
END IF
PRINT 19,K,X(K),COUNTSIM
19 FORMAT(I2,1X,F5.1,1X,I2)
20 CONTINUE
RETURN
END

C END OF IYCRS1L
C PROGRAM IYGSS3
C VARIABLES:

C G(56) -- EXPERIMENTAL DATA [INPUT]
C REF -- INDEX FOR IDENTIFYING TRMT(SMALL & LARGE)
C STOR1(28) -- TRMT 1(SMALL)
C STOR2(28) -- TRMT 2(LARGE)
C STOR11 -- REDUCED STOR1 DATA, 1ST ITER.
C STOR12 -- REDUCED STOR1 DATA, 2ND ITER
C STOR13 -- REDUCED STOR1 DATA, 3RD ITER.
C STOR14 -- REDUCED STOR1 DATA, 4TH ITER.
C STOR15 -- REDUCED STOR1 DATA, 5TH ITER.
C STOR21 -- REDUCED STOR2 DATA, 1ST ITER.
C STOR22 -- REDUCED STOR2 DATA, 2ND ITER.
C STOR23 -- REDUCED STOR2 DATA, 3RD ITER.
C STOR24 -- REDUCED STOR2 DATA, 4TH ITER.
C STOR25 -- REDUCED STOR2 DATA, 5TH ITER.

REAL G(56),REF,STOR1(28),STOR2(28),STOR11(15),
+ STOR12(15),STOR13(11),STOR14(11),STOR15(9),STOR21(19),
+ STOR22(19),STOR23(17),STOR24(17),STOR25(16),ST1(28),ST2(28)

INTEGER I,L

DATA STOR1/10,11,11,11,12,12,12,13,13,14,14,15,16,17,19/
DATA STOR2/10,11,11,12,13,13,14,14,15,16,17,17,19/
DATA STOR3/10,11,11,12,13,13,14,15,15,16,16,17,19/
DATA STOR4/10,11,11,12,13,13,14,15,16,16,17,19/
DATA STOR5/10,11,11,12,13,13,14,15,16,16,17,19/

DATA STOR11/10,12,13,13,14,14,15,16,17,18,20,22,24,26,
+ 27,28,30,41/
DATA STOR12/10,12,13,13,14,0,14,0,15,16,17,18,20,
+ 22,24,26,27,30,41/
DATA STOR13/10,12,13,13,14,15,16,17,18,20,22,
+ 24,26,27,28,30,41/
DATA STOR14/10,12,13,0,14,15,16,17,18,20,22,
+ 24,26,27,28,30,41/
DATA STOR15/10,12,13,14,15,16,17,18,19/1

DATA STOR21/10,12,13,13,14,14,15,16,17,18,20,22,24,26,
+ 27,28,30,41/
DATA STOR22/10,12,13,13,14,0,15,16,17,18,20,22,
+ 24,26,27,28,30,41/
DATA STOR23/10,12,13,13,14,15,16,17,18,20,22,
+ 24,26,27,28,30,41/
DATA STOR24/10,12,13,0,14,15,16,17,18,20,22,
+ 24,26,27,28,30,41/
DATA STOR25/10,12,13,14,15,16,17,18,20,22,24,26,27,28,30,41/

OPEN(138,FILE='gss3col',STATUS='OLD')
READ(138,*,END=11)(G(I),I=1,56)
DO 5 I=1,56
REF=MOD(I,2)
IF(REF.NE.0.0)THEN
  L=(I+1)/2
  STOR1(L)=G(I)
ELSEIF(REF.EQ.0.0)THEN
  L=I/2
  STOR2(L)=G(I)
END IF
IF(I.EQ.56)THEN
  PRINT 3
  FORMAT(/1X,'K',2X,'ST1',IX,'FR')
  CALL SORT(STOR1,28)
  PRINT 4
  FORMAT(/1X,'K',2X,'ST2',IX,'FR')
  CALL SORT(STOR2,28)
END IF
5 CONTINUE

DO 1 I=1,28
  ST1(I)=STOR1(I)
  WRITE(10,*)ST1(I)
1 CONTINUE

DO 2 J=1,28
  ST2(J)=STOR2(J)
  WRITE(20,*)ST2(J)
2 CONTINUE

CALL SELECT(STOR1,28)
  PRINT*, 'END OF SELECT 1'
CALL COMBINE(STOR1,15)
  PRINT*, 'END OF COMBINE 1'
CALL SELECT(STOR11,15)
  PRINT*, 'END OF SELECT 2'
CALL COMBINE(STOR12,11)
  PRINT*, 'END OF COMBINE 2'
CALL SELECT(STOR13,11)
  PRINT*, 'END OF SELECT 3'
CALL COMBINE(STOR14,9)
  PRINT*, 'END OF COMBINE 3'
C THIS SUBROUTINE USES EXCHANGE SORTING TECHNIQUE
C TO PRINT DATA IN ASCENDING ORDER; THIS PROCESS
C RECORDS THE NUMBER OF REPEATED VALUES AS INPUT TO
C INITIAL COUNTS & COMPARISONS

SUBROUTINE SORT (X,N)
REAL X(N),TEMP,TEMPO
INTEGER J,K,EXCHNG,COUNTSIM
COUNTSIM=0
EXCHNG=1

30 IF (EXCHNG.EQ.1) THEN
   EXCHNG=0
   DO 10 J=1,N-1
      IF(X(J).GT.X(J+1))THEN
10   CONTINUE
      ELSE
         EXCHNG=1
90   CONTINUE
      END IF
   END DO

10 CONTINUE

END
C THIS SUBROUTINE ZEROES REPEATED VALUES, REDUCING
C THE ORIGINAL DATA ARRAY TO UNIQUE, NON-REPEATED
C DATA POINTS

SUBROUTINE SELECT(Y,M)
REAL Y(M),V
INTEGER I
DO 2 I=1,M
V=Y(I)-Y(I+1)
IF(V)2,1,2
1 Y(I+1)=0.0
I=I+1
2 CONTINUE
PRINT 3,Y
3 FORMAT(F4.1)
RETURN
END

SUBROUTINE COMBINE(S,N)
REAL S(N)
INTEGER K
DO 5 K=1,N
IF(S(K).EQ.0.0)THEN
S(K)=S(K+1)
5 CONTINUE
RETURN
END
K=K+1
END IF
PRINT 4,S(K)
FORMAT(F4.1)
CONTINUE
RETURN
END

SUBROUTINE COMPARE(X,Y,M,N)
REAL X(M),Y(N),Z,C,LAMBDA
C=0.0
DO 8 J=1,M
DO 7 K=1,N
IF(C.EQ.0.0)THEN
LAMBDA=100.
END IF
Z=X(J)-Y(K)
IF(Z.EQ.0.0)THEN
C=C+1
LAMBDA=(1-C/28)*100
END IF
PRINT 6,J,K,X(J),Y(K),C,LAMBDA
FORMAT(2I3,1X,F4.1,3X,F4.1,1X,F3.0,1X,F5.1)
CONTINUE
CONTINUE
RETURN
END

C END OF IYGSS3

C PROGRAM IYVBS5
DIMENSION X(60),Y(60),Z(60),ZP(15),ZM(15),ZL(15),ZJ(15)
REAL X(1:15,1:4),Y(1:60),Z(1:60),DIFF,COUNTP,COUNTM,
+ COUNTL,COUNTJ, LAMBDAP,LAMBDAM,LAMBDAL,LAMBDAJ
INTEGER I,J,K,L,M

COUNTP=-22.
COUNTM=-24.
COUNTL=-20.
COUNTJ=-20.
F=15.

OPEN(190,FILE='vbs5',STATUS='OLD')
OPEN(191,FILE='vbs5',STATUS='OLD')
OPEN(192,FILE='vbs5cor',STATUS='OLD')

DO 50 J=1,4

DO 50 I=1,15

READ(190,90,END=21)X

90 FORMAT(F4.1,X,F4.1,X,F4.1,X,F4.1)

PRINT 1,X

1 FORMAT(F4.1)

DO 50 K=1,60

READ(191,91,END=22)Y

91 FORMAT(F4.1,X,F4.1,X,F4.1,X,F4.1)

PRINT 2

2 FORMAT(7X,'Peeler',5X,'Medium',7X,'Large',6X,'Jumbo')

PRINT 3,Y

3 FORMAT(4(7X,F4.1,X))

PRINT 4

4 FORMAT(7X,F4.1,1X)

DO 40 L=1,60

READ(192,90,END=23)Z(L)

IF(L.LE.15)THEN

ZP(L)=Z(L)

ELSEIF(L.GE.16.AND.L.LE.30)THEN

ZM(L-15)=Z(L)

ELSEIF(L.GE.31.AND.L.LE.45)THEN

ZL(L-30)=Z(L)

ELSEIF(L.GE.46.AND.L.LE.60)THEN

ZJ(L-45)=Z(L)

END IF

DO 30 M=1,60

DIFF=Z(L)-Y(M)

IF(DIFF.EQ.0.0)THEN

IF(L.GE.1.AND.L.LE.15)THEN

COUNTP=COUNTP+1

LAMBDAP=(1-COUNTP/F):;:100

ELSEIF(L.GE.16.AND.L.LE.30)THEN

COUNTP=COUNTP+1

LAMBDAP=(1-COUNTP/F)*100

ELSEIF(L.GE.31.AND.L.LE.45)THEN

COUNTP=COUNTP+1

LAMBDAP=(1-COUNTP/F)*100

ELSEIF(L.GE.46.AND.L.LE.60)THEN

COUNTP=COUNTP+1

LAMBDAP=(1-COUNTP/F)*100

END IF

END IF

90 FORMAT(F4.1,X,F4.1,X,F4.1,X,F4.1)
COUNTM=COUNTM+1
LAMBDAM=(1-COUNTM/F)*100
ELSEIF(L.GE.31.AND.L.LE.45)THEN
COUNTL=COUNTL+1
LAMBDAL=(1-COUNTL/F)*100
ELSEIF(L.GE.46.AND.L.LE.60)THEN
COUNTJ=COUNTJ+1
LAMBDAJ=(1-COUNTJ/F)*100
ELSE
END IF
END IF
PRINT 29,L,M,Z(L),Y(M),DIFF,COUNTP,
+ COUNTM,COUNTL,COUNTJ,LAMBDAP,
+ LAMBDAM, LAMBDAL,LAMBDAJ
29 FORMAT(2X,I2,1X,I2,1X,F4.1,1X,F4.1,1X,F5.1,
+ 2X,F4.0,1X,F4.0,1X,F4.0,1X,F4.0,2X,
+ F6.2,1X,F6.2,1X,F6.2,1X,F6.2)
IF(M.EQ.60)THEN
IF(L.EQ.15)THEN
CALL SORT(ZP,15)
ELSEIF(L.EQ.30)THEN
CALL SORT(ZM,15)
ELSEIF(L.EQ.45)THEN
CALL SORT(ZL,15)
ELSEIF(L.EQ.60)THEN
CALL SORT(ZJ,15)
ELSE
END IF
END IF
30 CONTINUE
40 CONTINUE
50 CONTINUE
21 CLOSE(190)
22 CLOSE(191)
23 CLOSE(192)
END

SUBROUTINE SORT(X,N)
REAL X(N),TEMP,TEMPO
INTEGER J,K,EXCHNG,COUNTSIM
COUNTSIM=0
EXCHNG=1
30 IF(EXCHNG.EQ.1)THEN
EXCHNG=0
DO 10 J=1,N-1
   IF(X(J).GT.X(J+1)) THEN
      TEMP=X(J)
      X(J)=X(J+1)
      X(J+1)=TEMP
      EXCHNG=1
   END IF
10 CONTINUE
GO TO 30
END IF

DO 20 K=1,N
   IF(X(K).EQ.X(K+1)) THEN
      COUNTSIM=COUNTSIM+1
      TEMPO=X(K+1)
      X(K)=TEMPO
   END IF
20 CONTINUE
PRINT 19,K,X(K),COUNTSIM
. 19 FORMAT(I2,1X,F4.1,1X,I2)
20 CONTINUE
RETURN
END

C END OF IYVBS5

C PROGRAM MACHDES

REAL HP,TE,VEL,L,KT,KX,KY,WB,WM,H,TP,TAM,TAC,ALPHA,SI
REAL COTTHET,R,RCF,D,MU,CW,THER,TANTHET,FH
PARAMETER(CW=0.10)

PARAMETER(KT=1.00, WB=1.75, WM=1.75, H=0.0, TAM=5.0, TAC=0.0, AI=2.15, SI=3.75, LT=7.5, KY=0.034, TP=50)

REAL SIGMAV, SIGMAVO, RHO, G, N, HO, ZO, VLOAD, SIGMAVB,
   L, VS, SUMSIGV, MEANSIG, THETA

REAL V(1:4,1:4), PHIDOT, SDOT, QXDOT, QYDOT, QZDOT,
   A(1:4,1:4), PHIDDOT, PHIDOTX, PHIDOTY, PHIDOTZ, SDDOT, QX,
   QY, QZ, S, U, T, PHIDDOTX, PHIDDOTY, PHIDDOTZ
INTEGER I

PARAMETER(UZ=1.0,Q1X=0,Q1Y=3.0125,Q1Z=0,U=1,
+ SDOT=159.92,SDDOT=15.99)

C SDOT IS IN IN PER MIN & SDDOT IN IN PER MIN PER MIN
C PARAMETER(RHO=720.15,G=9.81,SIGMAVO=0.0,
+ SIGMAVB=0.019733,B=0.0254,L=3.04,VS=0.0)

KX=0.00068*(WB+WM)+(AI/SI)

TE=LT*KT*(KX+WB*(KY+0.015))+WM*(LT*KY+H)+TP+TAM+TAC

VEL=0.0

PRINT*, 'VELO HP'

DO 10 I=1,150

HP=(TE*VEL)/33000

VEL=VEL+.25

PRINT 9,VEL,HP

9 FORMAT(F5.2,1X,F7.5)

10 CONTINUE

W=0.0

PRINT*, 'I J K W ALP PHI PE PH PL'

DO 40 I=1,25

ALPHA=0.0

DO 30 J=1,15

PHI=0

DO 20 K=1,20

ANGL1=PHI+ALPHA

ANGL2=ALPHA-PHI

ANGL3=PHI-ALPHA

DALPHA=2*ALPHA

WT=W*SIND(DALPHA/2)

PE=WT*TAND(ANGL1)

PH=WT*TAND(ANGL2)

PL=WT*TAND(ANGL3)

PRINT 19,1,J,K,W,ALPHA,PHI,PE,PH,PL

19 FORMAT(3(I2,1X),3(F5.2,1X),3(F8.4,1X))

PHI=PHI+2

20 CONTINUE

ALPHA=ALPHA+5

30 CONTINUE

W=W+1

40 CONTINUE

RCF=.500

PRINT*, 'R RCF D MU THET FH'

DO 70 K=1,10
R=2.9375
DO 60 I=1,10
D=0.625
    DO 50 J=1,5
        COTTHET=(SQRT((R+RCF)**2-(R+D/2)**2))/(R+D/2)
        MU=COTTHET
        TANTHET=1/MU
        THET=ATAND(TANTHET)
        FH=(CW*(MU*COS(THET)+SIN(THET)))/(COS(THET)
            -MU*SIN(THET))
        PRINT 49,R,RCF,D,MU,THET,FH
    49 FORMAT(4(F6.4,1X),F7.4,1X,F9.6)
    D=D+0.125
    50 CONTINUE
    R=R+.0625
  60 CONTINUE
RCF=RCF+0.0625
70 CONTINUE
.

SUMSIGV=0.0
THETA=30

DO 100 K=1,7
    HO=6*SIND(THETA)*0.0254
    Z0=(0.5*0.0254)/TAND(THETA)
    N=0.0
    DO 90 1=1,360
        Z=0.0
        DO 80 J=1,108
            IF(N.EQ.0)THEN
                SIGMA=SIGMAVO+RHO*G*(Z-ZO)
            END IF
            RH1=(RHO*G*(HO-Z))/(N-1)
            RH2=RHO*G*(HO-ZO)/(N-1)
            RH3=SIGMAVO-RH2
            RH4=((HO-Z)/(HO-ZO))**N
            SIGMAV=RH1+(RH3*RH4)
            SUMSIGV=SUMSIGV+SIGMAV
            REF=2.15-SIGMAV
            IF(REF.GE.0.0001.AND.REF.LE.0.001)THEN
                PRINT*,I,J,THETA,SIGMAV
                IF(J.EQ.108)THEN
                    MEANSIG=SUMSIGV/108
                    PRINT*,MEANSIG
            END IF
    70 CONTINUE
C SIGMA IS MAX (REACHES 2.15 KPA) @ N = 352; - N GIVES
C SIGMA TOO HIGH (@ HYDOSTATIC REF (N=0), SIGMA IS OVER-
C ESTIMATED).
Z = Z + 0.001
80 CONTINUE
N = N + 1
IF(N .EQ. 1) THEN
TERM = (HO - Z) / (HO - Z0)
RTERM = 1 / TERM
SIGMAV = SIGMAVO * TERM + RHO * G * (HO - Z) * LOG(RTERM)
END IF
90 CONTINUE
VLOAD = MEANSIG * B * L + VS
PRINT*, VLOAD
THETA = THETA + 5
100 CONTINUE
T = 0
PRINT*,'  I  T  QX  QY  QZ'
C POSITION IN TIME OF A PARTICLE FOLLOWING A SCREW
C PATH IN A CYLINDRICAL ROLLER SORTER OF GIVEN
C DIAMETER
DO 110 I = 1, 400
S = 0.30 * T
QX = COS(T) * Q1X - SIN(T) * Q1Y
QY = SIN(T) * Q1X + COS(T) * Q1Y
QZ = Q1Z + S * U
PRINT 7, I, T, QX, QY, QZ
7 FORMAT(I3, 1X, F4.1, 1X, 3(F7.4, 1X))
T = T + 1
110 CONTINUE
C ANGULAR VELOCITY
PHIDOT = 20.00
PRINT*, ' I PHIDOT PHIDOTX PHIDOTY PHIDOTZ'
DO 115 I = 1, 31
PHIDOTX = PHIDDT ** 2 * Q1X
PHIDOTY = PHIDDT ** 2 * Q1Y
PHIDOTZ = SPD ** 2 * Q1Z
PRINT 119, I, PHIDOT, PHIDOTX, PHIDOTY, PHIDOTZ
PHIDOT = PHIDOT + 1
CONTINUE

C LINEAR VELOCITY
V(1,1)=0.0
V(2,2)=0.0
V(3,3)=0.0
V(4,1)=0.0
V(4,2)=0.0
V(4,3)=0.0
V(4,4)=0.0
V(1,2)=PHIDOT
V(1,3)=0.0
V(1,4)=0.0
V(2,1)=PHIDOT
V(2,3)=0.0
V(2,4)=0.0
V(3,1)=0.0
V(3,2)=0.0
V(3,4)=SDOT

C PHIDOT IS IN RPM
PHIDOT=20.0
PRINT*/I PHIDOT QXDOT QYDOT QZDOT'

DO 120 I=1,31
QXDOT=-PHIDOT*Q1Y
QYDOT=PHIDOT*Q1X
QZDOT=SDOT
PRINT 119,1,PHIDOT,QXDOT,QYDOT,QZDOT

119 FORMAT(I2,1X,F5.2,1X,3(F8.2,1X))
PHIDOT=PHIDOT+1

CONTINUE

C ANGULAR ACCELERATION
PHIDOT=20.0
PRINT*, 'I PHIDOT PHIDOTX PHIDOTY PHIDOTZ'

DO 125 DO I=1,31
PHIDDOTX=-PHIDOT**2*Q1X-PHIDDOT*Q1Y
PHIDDOTY=PHIDDOT*Q1X-PHIDOT**2*Q1Y
PHIDDOTZ=0
PRINT 119,1,PHIDOT,PHIDDOTX,PHIDDOTY,PHIDDOTZ
PHIDOT=PHIDOT+1

CONTINUE

C LINEAR ACCELERATION

A(4,1)=0.0
A(4,2)=0.0
A(4,3)=0.0  
A(4,4)=0.0  
A(1,4)=0.0  
A(2,4)=0.0  
A(3,4)=SDDOT+SDOT  
A(1,1)=-(PHID0T**2+PHIDD0T)  
A(1,2)=0.0  
A(1,3)=0.0  
A(2,1)=PHIDDOT  
A(2,2)=-PHIDOT**2  
A(2,3)=0.0  
A(3,1)=0.0  
A(3,2)=0.0  
A(3,3)=0.0  
PHIDOT=20.00  
PHIDDOT=2.00  
PRINT*,' I PHIDOT QXDOT QYDOT QZDOT'  
DO 130 1=1,31  
QXDDOT=-(PHIDOT**2+PHIDDOT)*Q1X  
QYDDOT=-PHIDOT**2*Q1Y  
QZDDOT=(SDDOT+SDOT)*Q1Z  
PRINT 119,I,PHIDOT,QXDDOT,QYDDOT,QZDDOT  
PHIDOT=PHIDOT+1  
130 CONTINUE  
C SPATIAL DESCRIPTION OF A HELICAL PATH  
CALL HELIX  
CALL DISPINV  
END  
SUBROUTINE HELIX  
REAL X,Y,Z,A,B,T,LENGTH,REVS  
INTEGER I  
PARAMETER(A=3.3125,B=0.30)  
T=0.0  
PRINT*,' I T X Y Z LENGTH REVS'  
DO 10 I=1,1509  
X=A*COS(T)  
Y=A*SIN(T)  
Z=B*T  
LENGTH=SQR(1+B)*T  
REVS=T/(2*3.14159)  
PRINT 9,I,T,X,Y,Z,LENGTH,REVS
SUBROUTINE DISPINV

REAL S(4,4), SI(4,4), SSI(4,4)

REAL SUMTERM, TERM

INTEGER I, J, K, M, N

PARAMETER(M=4, N=4)

S(1,1) = 3.05101
S(1,2) = 2.30784
S(1,3) = 1.20031
S(1,4) = -0.0967235
S(2,1) = 1.28995
S(2,2) = 2.37624
S(2,3) = 3.08738
S(2,4) = 3.31109
S(3,1) = 0.12
S(3,2) = 0.24
S(3,3) = 0.36
S(3,4) = 0.48
S(4,1) = 0.0
S(4,2) = 0.0
S(4,3) = 0.0
S(4,4) = 1.

SI(1,1) = -3.3125
SI(1,2) = 0.0
SI(1,3) = 0.0
SI(1,4) = -3.3125 * 1.203
SI(2,1) = 3.05101
SI(2,2) = 1.28995
SI(2,3) = 0.12
SI(2,4) = -(3.05101 * 1.20031 + 1.28995 * 3.08738 + 0.12 * 0.36)
SI(3,1) = 2.30784
SI(3,2) = 2.37624
SI(3,3) = 0.24
SI(3,4) = -(2.30784 * 1.20031 + 2.37624 * 3.08738 + 0.24 * 0.36)
SI(4,1) = 0.0
SI(4,2) = 0.0
SI(4,3) = 0.0
SI(4,4) = 1.0

DO 30 I = 1, M
K=I
SUMTERM=0.0

5      DO 20 J=1,N
     TERM=S(I,J)*SI(J,K)
     SUMTERM=SUMTERM+TERM
     PRINT 19,I,J,K,TERM,SUMTERM
19    FORMAT(3(I1,1X),2(F9.5,1X))
     IF(J.EQ.4)THEN
     SUMTERM=0.0
     END IF
20    CONTINUE

K=K+1
IF(K.LE.4)THEN
GO TO 5
END IF
30    CONTINUE

PRINT 50,S,SI,SSI
50   FORMAT(/4(4F10.5/)/,4(4F10.5)/,4(4F10.5)/)
RETURN
END

C END OF MACHDES

C PROGRAM OPDPEL
REAL D1,D2,N,PP,QQ
REAL K(1:4),P(1:4),W(1:4),C1(1:10),C2(1:10),
+ C3(1:10),C4(1:10),PG(1:4),DENOM,SUMC1,SUMC2,SUMC3,SUMC4,
+ CW,PW,SUMCPW,G1(1:4),Q,EW,SW

DATA D1,D2,D4,D5/0.625,0.757,1.000,1.125/
PARAMETER(N=5,PP=-.004666,QQ=.0011666)
PARAMETER(Q=5)
CALL PQ (N,D1,D2,D4,D5)

C OPTIMUM DIAMETER
DO 10 I=N,1,-1
   D=D1+(I-1)*((D2-D1)+(I-2)*(PP+(I-3)*QQ))
   PRINT*,D
10    CONTINUE
DATA K/5,1,1.5,2.0/
DATA P/125,.375,.375,.125/
DATA C1/0,.005,.005,.005,.005,.005,.005,.005,.005,.005/
DATA C2/.004,.004,.004,.004,.004,.004,.004,.004,.004,.004/
DATA C3/.003,.003,.003,.003,.003,.003,.003,.003,.003,.003/
DATA C4/.002,.002,.002,.002,.002,.002,.002,.002,.002,.002/
DATA PG/.95,.96,.97,.98/
DATA GI/60,1.93,1.81,64/

C PELEG'S CRITERIA
DENOM=K(1)*P(1)+K(2)*P(2)+K(3)*P(3)+K(4)*P(4)
W(1)=K(1)*P(1)/DENOM
W(2)=K(2)*P(2)/DENOM
W(3)=K(3)*P(3)/DENOM
W(4)=K(4)*P(4)/DENOM
PRINT*,W(1),W(2),W(3),W(4)
SUMC1=0.0
SUMC2=0.0
SUMC3=0.0
SUMC4=0.0

DO 20 I=1,10
  SUMC1=SUMC1+C1(I)
  SUMC2=SUMC2+C2(I)
  SUMC3=SUMC3+C3(I)
  SUMC4=SUMC4+C4(I)
20 CONTINUE

PRINT*,SUMC1,SUMC2,SUMC3,SUMC4
CW=SUMC1*W(1)+SUMC2*W(2)+SUMC3*W(3)+SUMC4*W(4)
PW=PG(1)*W(1)+PG(2)*W(2)+PG(3)*W(3)+PG(4)*W(4)
SUMCPW=CW+PW
PRINT*,CW,PW,SUMCPW
EW=0.0

DO 30 J=1,4
  EW=EW+(PG(J)*GI(J)*W(J))/(Q*P(J))
30 CONTINUE

SW=1-EW
PRINT*,EW,SW
END

SUBROUTINE PQ (M,DD1,DD2,DD4,DD5)
REAL M,A1,B1,A2,B2,C1,C2,DET,PP,QQ
A1=(M-1)*(M-2)
B1=(M-1)*(M-2)*(M-3)
A2=(M-2)*(M-3)
B2=(M-2)*(M-3)*(M-4)
C1=DD5-DD1-(M-1)*(DD2-DD1)
C2=DD4-DD1-(M-2)*(DD2-DD1)
DET=A1*B2-A2*B1
PP=(C1*B2-C2*B1)/DET
QQ=(A1*C2-A2*C1)/DET
PRINT*,PP,QQ
RETURN
END

C END OF OPDPEL

APPENDIX B. Data

B.1 Random measurements of crawfish body weight (g) at the Ben Hur Aquaculture Facility (n = 552).

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Sample crawfish body weight (g) ... cont’d.

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B.2. Calibration Data

B.2.1 Cylindrical roller sorter

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B.2.2. Diverging vane belt sorter

Measured time in seconds per complete revolution of vane belt pulley (total distance equals 178.5 in with speed computed in ft/min in parenthesis)

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B.3 Body weight, total body length, carapace width, and carapace depth

Measurements on crawfish weight (g), total body length (mm), carapace depth (cm), and carapace width (cm).

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B.4. Crawfish particle density

Measurements on crawfish weight (g) and volume of water displaced (ml).
### B.5. Angle of repose on PVC surface

Measurements on angle of repose and crawfish weight on PVC surface.

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<td>Angle, degrees</td>
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<td>6</td>
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### B.7. Test data for cylindrical roller sorter

Test 1: Sample crawfish weight (g) for left pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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74.0 94.0 105.0 130.0
72.0 90.0 97.0 105.0
74.0 91.0 90.0 103.0
76.0 92.0 95.0 105.0
78.0 84.0 96.0 111.0
76.0 84.0 86.0 90.0
82.0 81.0 89.0 101.0
Test 1: Sample crawfish weight (g) for right pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

| 0.0 92.0 | 100.0 | 111.0 |
| 0.0 84.0 | 79.0  | 90.0  |
| 0.0 91.0 | 88.0  | 91.0  |
| 0.0 80.0 | 87.0  | 95.0  |
| 0.0 82.0 | 90.0  | 97.0  |

| 76.0 81.0 | 90.0  | 90.0  |
| 74.0 88.0 | 92.0  | 100.0 |
| 72.0 71.0 | 90.0  | 103.0 |
| 0.0 81.0 | 80.0  | 98.0  |
| 0.0 85.0 | 90.0  | 106.0 |
| 0.0 87.0 | 76.0  | 90.0  |
| 0.0 85.0 | 87.0  | 96.0  |
| 0.0 90.0 | 100.0 | 109.0 |
| 0.0 86.0 | 92.0  | 89.0  |
| 0.0 86.0 | 81.0  | 93.0  |
| 0.0 80.0 | 97.0  | 101.0 |
| 0.0 76.0 | 96.0  | 100.0 |
| 0.0 74.0 | 90.0  | 90.0  |
| 0.0 85.0 | 82.0  | 106.0 |
| 0.0 93.0 | 92.0  | 81.0  |

Test 2: Sample crawfish weight (g) for left pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

| 72.0 95.0 | 99.0  | 98.0  |
| 76.0 85.0 | 90.0  | 105.0 |
| 74.0 93.0 | 90.0  | 100.0 |
| 77.0 91.0 | 95.0  | 106.0 |
| 76.0 90.0 | 90.0  | 90.0  |
| 78.0 89.0 | 99.0  | 89.0  |
| 80.0 85.0 | 79.0  | 100.0 |
| 74.0 80.0 | 102.0 | 91.0  |
| 76.0 96.0 | 100.0 | 85.0  |
| 78.0 95.0 | 84.0  | 95.0  |
| 69.0 84.0 | 86.0  | 88.0  |
| 76.0 80.0 | 95.0  | 99.0  |
| 0.0 85.0 | 90.0  | 85.0  |
| 0.0 90.0 | 80.0  | 95.0  |
| 0.0 76.0 | 100.0 | 95.0  |
Test 2: Sample crawfish weight (g) for right pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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<th>Medium</th>
<th>Large</th>
<th>Jumbo</th>
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<td>97.0</td>
<td>138.0</td>
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<td>86.0</td>
<td>91.0</td>
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<td>95.0</td>
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<td>100.0</td>
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Test 3: Sample crawfish weight (g) for left pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Peeler</th>
<th>Medium</th>
<th>Large</th>
<th>Jumbo</th>
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Test 3: Sample crawfish weight (g) for right pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Peeler</th>
<th>Medium</th>
<th>Large</th>
<th>Jumbo</th>
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Test 4: Sample crawfish weight (g) for left pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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Test 4: Sample crawfish weight (g) for right pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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</table>

Test 5: Sample crawfish weight (g) for left pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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</table>

Test 5: Sample crawfish weight (g) for right pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

<table>
<thead>
<tr>
<th>78.0</th>
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Test 6: Sample crawfish weight (g) for left pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

12.5 28.3 29.9 51.3
13.0 22.0 24.6 45.1
12.0 19.2 43.4 26.6
6.6 21.9 35.9 34.0
12.9 20.4 29.7 68.4
12.9 19.4 27.6 94.2
11.3 24.0 18.9 17.6
15.5 12.7 25.4 33.9
11.8 19.1 28.6 61.1
15.5 16.7 20.8 33.3
13.3 19.0 33.2 43.5
10.4 18.6 18.7 44.8
13.7 17.1 22.4 29.1
7.7 23.9 24.0 27.4
12.0 24.1 15.6 32.4

Test 6: Sample crawfish weight (g) for right pair of roller for cylindrical roller sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

16.9 15.6 27.7 53.9
10.5 16.3 26.3 49.0
15.7 17.3 28.3 33.4
18.7 17.2 15.4 36.3
14.3 13.9 45.4 36.7
11.6 14.1 35.5 35.4
15.8 14.2 23.1 29.1
13.0 26.5 20.8 20.1
11.4 36.5 41.5 30.3
14.7 27.3 20.5 20.8
14.7 22.1 29.2 41.5
9.9 17.0 28.7 31.6
12.9 19.6 21.1 35.7
13.8 24.1 51.5 58.8
10.8 23.7 29.6 29.6

B.8. Test data for diverging vane belt sorter

Test 4: Sample crawfish weight (g) for vane belt sorter (column 1 to left
represents peeler, followed by medium, large, and jumbo; 15 observations each column)
15.9 22.0 27.3 42.5
19.8 22.7 22.8 58.8
16.0 18.2 24.3 43.5
14.8 19.8 30.4 50.3
15.5 22.4 31.3 59.4
13.1 26.6 30.9 69.3
18.2 23.9 29.2 35.3
14.0 23.7 26.3 29.8
11.2 26.8 25.4 38.2
16.7 30.7 30.8 41.9
14.5 24.5 38.0 29.3
12.1 16.7 30.5 62.5
10.7 27.9 25.5 37.2
14.3 20.6 28.7 48.6
12.9 24.3 22.8 45.2

Test 5: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)
12.0 16.0 26.0 22.0
12.0 14.0 16.0 48.0
11.0 11.0 19.0 25.0
12.0 18.0 20.0 23.0
12.0 17.0 25.0 22.0
16.0 13.0 20.0 43.0
11.0 17.0 22.0 37.0
14.0 16.0 18.0 47.0
27.0 13.0 20.0 37.0
18.0 11.0 24.0 57.0
15.0 14.0 29.0 48.0
19.0 13.0 17.0 26.0
16.0 14.0 16.0 37.0
12.0 14.0 19.0 22.0
12.0 14.0 16.0 35.0

Test 6: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)
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13.0 19.0 22.0 37.0
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Test 7: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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Test 8: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)

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| Test 11: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column) |
|---|---|---|---|
| 11.0 | 11.0 | 17.0 | 38.0 |
| 12.0 | 14.0 | 24.0 | 25.0 |
| 12.0 | 16.0 | 22.0 | 22.0 |
| 11.0 | 23.0 | 22.0 | 33.0 |
| 11.0 | 20.0 | 12.0 | 16.0 |
| 12.0 | 20.0 | 24.0 | 33.0 |
| 16.0 | 14.0 | 21.0 | 21.0 |
| 12.0 | 16.0 | 21.0 | 15.0 |
| 13.0 | 11.0 | 11.0 | 22.0 |
| 12.0 | 16.0 | 22.0 | 33.0 |
| 11.0 | 16.0 | 18.0 | 15.0 |
| 12.0 | 12.0 | 20.0 | 16.0 |
| 11.0 | 21.0 | 20.0 | 31.0 |
| 14.0 | 18.0 | 13.0 | 23.0 |
6.0 22.0 15.0 20.0

Test 12: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)
13.0 23.0 23.0 46.0
13.0 18.0 24.0 66.0
15.0 13.0 12.0 50.0
12.0 22.0 21.0 31.0
17.0 17.0 38.0 52.0
13.0 15.0 29.0 14.0
13.0 20.0 24.0 16.0
12.0 31.0 27.0 20.0
14.0 23.0 20.0 27.0
13.0 21.0 15.0 20.0
13.0 6.0 16.0 20.0
6.0 13.0 17.0 34.0
14.0 11.0 32.0 27.0
12.0 24.0 22.0 29.0
14.0 23.0 23.0 25.0

Test 13: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)
14.0 17.0 22.0 46.0
10.0 24.0 24.0 55.0
10.0 18.0 13.0 38.0
14.0 14.0 12.0 16.0
12.0 17.0 21.0 68.0
13.0 20.0 16.0 38.0
16.0 15.0 11.0 45.0
16.0 18.0 15.0 30.0
12.0 14.0 25.0 52.0
14.0 18.0 17.0 32.0
14.0 21.0 21.0 14.0
12.0 13.0 17.0 12.0
10.0 16.0 25.0 44.0
12.0 16.0 24.0 15.0
11.0 20.0 15.0 15.0

Test 14: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)
15.9 22.0 27.3 42.5
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<th>Test 15: Sample crawfish weight (g) for vane belt sorter (column 1 to left represents peeler, followed by medium, large, and jumbo; 15 observations each column)</th>
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**B.9. Test data for grid shaker sorter**

Test 1: Sample crawfish weight (g) data for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

<p>| 13 | 56 |
| 20 | 25 |
| 17 | 24 |
| 28 | 40 |
| 19 | 45 |</p>
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<th>Test 2: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).</th>
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Test 2: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).
Test 3: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

| 13 26 |
| 14 32 |
| 13 18 |
| 13 20 |
| 18 19 |
| 13 29 |
| 15 15 |
| 11 22 |
| 10 20 |
| 11 18 |
| 10 24 |

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| 11 41 |
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| 12 27 |
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| 14 20 |
| 19 30 |
| 17 30 |
| 17 12 |
| 15 14 |
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| 12 17 |
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| 13 16 |
| 14 14 |
| 16 13 |
| 11 13 |
| 16 10 |
| 12 15 |
| 10 14 |
| 13 13 |
**Test 4**: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

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**Test 5**: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

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Test 6: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

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Test 7: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

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| 16 | 36 |

Test 9: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).
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Test 10: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).
Test 11: Sample crawfish weight (g) for grid shaker sorter (column 1 to left represents small size and column 2 represents large size of crawfish, 28 observations each column).

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Draft ASAE Standard

PERFORMANCE TEST AND EVALUATION

OF CRAWFISH SORTING MACHINES

October, 1995

Proposed by the Committee on Aquaculture Machinery
for consideration by the ASAE Criteria and Standard Committee

SECTION 1 -- PURPOSE AND SCOPE

1.1 The purpose of this standard is to establish a uniform method of determining the sorting capacity, sorting efficiency and sorting loss of crawfish sorting machines. This Standard aims to provide a basis for comparing the performance of crawfish sorter prototypes or commercial models, thereby setting a workable design objective.

1.2 This Standard pertains to aquacultural machinery designed to sort crawfish into market grades (peelers, medium, large, and jumbo). The mechanism of sorting may use any or combinations of the following:
diverging clearance cylindrical rollers, V-section diverging clearance belts,
vibrating parallel bars, water-immersed passive parallel bars, rotary water-
immersed parallel bars, counterweight balance method.

SECTION 2 -- DEFINITIONS

2.1 Sorting: The process of separating materials or products into
various size groups by passing the same into a constricted space (or by other
suitable means) and making use of its differentiating characteristic (length,
width, weight, etc.) to obtain segregation into size groups.

2.2 Capacity: The weight of material or product per unit time collected
at the sorter outlets, kg/min (lb/min). Details are explained in detail in
section 4.6

2.3 Sorting efficiency: The degree of product or material uniformity
within a particular size group. This is closely related to the goodness of
separation between size groups.

2.3 Sorting loss: The degree of product or material contamination within
a particular size group. Also, the amount of material actually damaged or
lost during the sorting process.

2.4 Coefficient of separability $\lambda$: The ratio of product or material
contaminants (product or material entering the wrong outlet) to the amount
of product or material in a particular size group.
SECTION 3 -- TEST CONDITIONS

3.1 The sorter machine to be tested shall be in good mechanical condition and shall be properly adjusted.

3.2 Tests may be conducted on a sorting machine (new or existing) to evaluate its performance, to upgrade design, or to make recommendations relative to on-site operating conditions.

3.3 The geometric, physico-mechanical, and dynamic specifications shall be checked with the machine suitably mounted on hard surface in normal operating position. Dimensions shall be measured consistent with the spatial configuration of the sorter machine.

3.4 If a manufacturer's current production model will be compared with those of other manufacturers then he must be notified well in advance of the test. He may then arrange to have his representative be present during the test.

3.5 Crawfish samples newly harvested from ponds shall be made available in marked sacks weighing 38 to 42 lb each. Preliminary statistical information on the frequency distribution with respect to size and weight shall be obtained by random piece by piece careful measurement.

SECTION 4 -- TEST PROCEDURE

4.1 Guidelines for test setup

4.1.1 The accuracy of the tests can be influenced by sampling
procedure, machine adjustments, and hopper design. The following recommendations should be followed to maintain test accuracy:

4.1.1.1 Crawfish samples should be fairly representative of the total mass of crawfish being marketed or distributed. Pond collection scheme should, therefore, be distributed over the entire area of catch or harvest. At the test site crawfish should be mixed in container tubs or buckets, and must be washed and rid of unwanted debris (vegetation, excess bait, etc.).

4.1.1.2 Sorting machine adjustments should match the requirements for sorting. The primary adjustments are as follows: clearance between sorting space, machine speed, and intensity of vibration.

4.1.1.2.1 If the sorting machine is of the cylindrical roller type rpm should not exceed 50 and may well be within the range 40 to 45; hopper vibration intensity should be moderately fast (setting = 6), inclined approximately 10° with respect to the horizontal plane, and opened at least 8 cm (3 in.) but not to exceed 22 cm (9 in.); roller clearance at the narrow end should be 11.3 mm (0.445 in.) and at the wide end 25.37 mm. Clearances may be widened no more than 2 mm (1/16 in.) to accommodate bigger crawfish samples.

4.1.1.2.2 If the sorting machine type is shaker tray with parallel tubes vibration intensity should be moderately fast to fast (setting of at least 8); clearance between tubes or bars should be 2.21333 cm (0.87139 in). Clearances may be widened no more than 5 mm to accommodate bigger
4.1.2.3 If the sorting machine type is a diverging vane belt linear speed of travel must be between 14 to 18 m/min (45 to 60 ft/min); included angle between the V-section of the pair of belts should not exceed 110°, with clearance between belts equal to 1.50 cm (0.59375 in.) at the narrow end and 2.8575 cm (1.125 in.) at the wide end; and, hopper opening should be equal to 10.16 cm (4 in.), moderately fast intensity of vibration (setting equal to 7) with the same angle if inclination as the cylindrical roller sorter machine.

4.1.3 Hoppers should ensure a steady, uniform discharge of crawfish into the sorting chamber. Intermittent flow of crawfish, falling as large clumps into the sorting chamber introduces inaccurate results. If the hopper is not mechanically agitated it will help if a machine assistant stands close by to break up crawfish clumps as they emerge from the hopper.

4.1.4 Tests shall be run with the crawfish sorter hopper filled and leveled to 40 to 50% capacity as defined by ASAE Standard S281, Capacity designation for Fertilizer and Pesticide Hoppers and containers.

4.2 Collection devices and sample handling

4.2.1 After completing preparation of samples (4.1.1.1) these should be loaded in container baskets measuring 30.5 cm x 30.5 cm x 61 cm (1 ft. x 1 ft x 2 ft). These container baskets must be perforated on all sides and can be opened by suitable spring latches on any 3 sides. The reason for this is...
crawfish samples for piece by piece measurement can be drawn from any
three opening, saving time in mixing the batch of crawfish from time to
time. Bigger crawfish tend to migrate quickly to the upper layers; this error
is reduced by drawing samples from different location at a time.

4.2.2 Live crawfish samples need to be kept fresh. They should be
periodically sprayed with water while in container boxes or covered with
moistened jute sacks. If actual test is not conducted during the hour,
crawfish samples should be kept in coolers and withdrawn at definite time
intervals for rewetting.

4.3 **Instruments for measurement**

4.3.1 Digital weighing instruments for crawfish can be divided into two
classes: 150 to 250 g range for individual measurements and 20 to 25 kg
range for sorting output measurement. Both types of weighing devices
should have wide weighing platforms and should be water resistant. When
taking crawfish sample weights it is recommended that crawfish be placed
in rigid plastic containers to minimize weighing scale drift as a result of
bodily movements of crawfish.

4.3.2 Measuring board for taking body length should be available. For
carapace width and carapace depth a handheld direct vernier is needed.
Length measurements should be made with the crawfish sample completely
stretched out on the measuring board, with the tail spread out at the lower
extremity. Carapace depth should include the 2nd pair of legs and carapace
width should be taken without any perceptible deformation of the crawfish
shell.

4.4 Description of the test procedure.

The test consists of three parts: (1) determination of the frequency
distribution of bodily dimensions (total body length, carapace width,
carapace depth) and weight, (2) determination of capacity, and (3)
determination of sorting efficiency as indicated by the coefficient of
separability.

4.5 Frequency distribution

4.5.1 From a container box of crawfish randomly draw samples (from
any three outlet as described 4.2.1) and record its weight and bodily
dimensions using the measuring devices mentioned in 4.3.2. Repeat the
process till a minimum of 1000 samples (state reference here) have been
inspected. Using the data thus obtained plot frequency histograms of the
crawfish sample.

4.5.2 Subsequent crawfish samples drawn from sorter outlets should
closely approximate the distribution obtained in 4.5.1. If the sample
distribution is approximately normal then more middle-sized crawfish is to
be expected from the sorter machine outlets. If the sample distribution is
skewed then crawfish from sorter machine outlets should correspondingly
reflect either more or less of small or large crawfish, whichever is the case.

4.6 Determination of capacity
4.6.1 Initial weight of the sample crawfish is taken before loading into the sorter hopper. The amount of crawfish may vary but it would be convenient to use one sack per test run since crawfish farmers normally fill their catch in such sacks (38 to 45 lb).

4.6.1 To ensure smooth flow crawfish samples should be loaded into hoppers as uniformly as possible, not dumped abruptly.

4.6.2 Time measurement commences as soon as the hopper sliding gate is opened to a height recommended by the machine manufacturer. For a one-sack hopper volume hopper opening should be at least 3 in.

4.6.3 Sorter capacity should be calculated as follows:

\[ QP_i = F_i + P_g G_i \]

where

- \( Q \) = inflow rate, kg/min (lb/min)
- \( P_i \) = fractions of raw material grade distribution as sampled in the raw material conduit
- \( F_i \) = rate of flow of fraction i which does not reach its intended destination in an outflow conduit i, kg/min (lb/min)
- \( P_g \) = pure product fractions of grade i
- \( G_i \) = rate of outflow in conduit i, kg/min (lb/min)

4.7 Determination of coefficient of separability

4.7.1 Coefficient of separability is an index that measures how good the process of sorting is with respect to a differentiating character of the sample
(bodily dimensions). It is computed from the following equation:

\[ \lambda = 1 - \frac{\Delta}{\Delta_0} \]

where

- \( \lambda \) = coefficient of separability
- \( \Delta \) = number of identical dimensions in outflow conduits
- \( \Delta_0 \) = number of samples in outflow mix

4.7.1.1 If a sample outflow conduit shares no identical values or dimensions with the other sample outflow conduits then \( \lambda = 1 \) and separation is perfect; if \( \lambda = 0 \), the mixture is inseparable.

4.7.1.2 If a sample outflow conduit shares all identical values or dimensions with other sample outflow conduits then \( \lambda = 0 \) and there's no separation; or, sorting was unable to separate the sample mix into different size groups based on a differentiating characteristic.

4.7.1.3 Values for \( \lambda \) may be converted to percentage by multiplication by 100.

SECTION 5 – METHOD OF REPORTING RESULTS

5.1 If the test has been conducted as described by this standard, the test results should be identified as follows:

5.1.1 The following shall be placed on each page on which the test results appear: "these results have been obtained from a test made in
accordance with ASAE Standard _____, Performance Test and Evaluation of Crawfish sorting machines”.

5.1.2 A descriptive statement shall be included in the report to explain the coefficient of separability. For example: This 91% separability means that for every 100 kg sorter grade outflow 9 kg would be expected to fall into grades outside of the grade in consideration.

5.2 A brief description of the sorter shall precede the dimensions. The following data, where appropriate, should be included in the description:

- Type (cylindrical roller, vibrating parallel tubes, diverging V-belt, etc)
- Manufacturer’s name, model number, and year of manufacture: (serial number if available)
- Minimum and maximum capacity
- Minimum and maximum separability
- Manufacturer’s recommended clearance (narrow end):
- Manufacturer’s recommended clearance (wide end):
- Manufacturer’s recommended vibration setting:
- Manufacturer’s recommended hopper opening height:
- Manufacturer’s recommended speed
- Manufacturer’s recommended included angle of V belt.

Overall length: cm (in.)
Overall height: cm (in.)
Overall width: cm (in.)
Hopper capacity: m$^3$ and kg (ft$^3$ and lb)

Hopper geometry (shape, angle of inclination, vibrated or not, etc)

5.3 All test results shall be stated as listed in paragraph 5.1 and include the following:

- Crawfish tested (average weight, average length, average carapace depth, average carapace width, standard deviation and % CV of data)
- Operating speed (rpm if roller sorter, linear speed if belt sorter)
- Clearance between sorting space
- Intensity of vibration (rpm of motor, maximum amplitude)
- Included angle of belt V-section
- Height of hopper opening
- Capacity computation sheet
- Coefficient of separability computation sheet
- Information concerning exceptions or additions which are peculiar to this test

Cited Standards:

ASAE S281, Capacity Designation for Fertilizer and Pesticide Hoppers and Containers
D. Expressions for volumetric capacity and torque

D.1 Cylindrical roller cylinder sorter (with helical grooves)

Table 1. Variables in the cylindrical roller sorter and their dimensions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description of quantity</th>
<th>Dimension</th>
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<tbody>
<tr>
<td>P</td>
<td>Pitch of screw, in.</td>
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<tr>
<td>(D_{\text{ave}})</td>
<td>Average diameter of cylinder, in.</td>
<td>L</td>
</tr>
<tr>
<td>(D_s)</td>
<td>Shaft diameter, in</td>
<td>L</td>
</tr>
<tr>
<td>(L_r)</td>
<td>Length of cylinder roller, in.</td>
<td>L</td>
</tr>
<tr>
<td>Ch</td>
<td>Clearance of hopper end, in.</td>
<td>L</td>
</tr>
<tr>
<td>Co</td>
<td>Clearance at outlet end, in.</td>
<td>L</td>
</tr>
<tr>
<td>N</td>
<td>Rotational speed of roller, rpm</td>
<td>T(^{-1})</td>
</tr>
<tr>
<td>G</td>
<td>Acceleration due to gravity, in/sec(^2)</td>
<td>LT(^{-2})</td>
</tr>
<tr>
<td>T</td>
<td>Torque required to operate sorter, in-lb</td>
<td>FL</td>
</tr>
<tr>
<td>Q</td>
<td>Volumetric capacity, in³/min</td>
<td>L(^3) T(^{-1})</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Bulk density of material, lb/in³</td>
<td>(\rhoFL_{-3})</td>
</tr>
<tr>
<td>(\mu)</td>
<td>Coefficient of friction, crawfish on roller</td>
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</tr>
</tbody>
</table>

Writing an expression for volumetric capacity \(Q\) in terms of the other variables the general functional relationship is

\[
Q = f(P, D_{\text{ave}}, D_s, L_r, C_h, C_o, N, G, T, \rho, \mu).
\] (1)
Buckingham's Pi Theorem states that it is possible to form a total of 8 dimensionless groups (not counting μ which is already dimensionless) from the 11 quantities involved, using 3 basic dimensions (FLT system) or,

\[ s = n - b \]
\[ = 11 - 3 \]
\[ = 8. \]

Dividing (1) by \( Q \) and denoting exponents of variables as \( C_i \)'s we obtain

\[ 1 = C_a Q^{C_1} P^{C_2} D_{ave}^{C_3} D_s^{C_4} L_r^{C_5} C_h^{C_6} C_s^{C_7} N^{C_8} G^{C_9} T^{C_{10}} \rho^{C_{11}} \] (2)

Writing (2) in terms of its dimensions we have

\[ 0 = (LT^{-1})^{C_1} (L)^{C_2} (L)^{C_3} (L)^{C_4} (L)^{C_5} (L)^{C_6} (L)^{C_7} (T^{-1})^{C_8} (LT^2)^{C_9} (FL)^{C_{10}} (FL)^{C_{11}} \]

The corresponding auxiliary equations are as follows:

\[ \text{F: } 0 = C_{10} + C_{11} \] (3)

\[ \text{L: } 0 = 3C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 + C_{10} - 3C_{11} \] (4)

\[ \text{T: } 0 = -C_1 - C_8 - 2C_9 \] (5)

Arbitrarily assign values to \( C_2, C_3, C_4, C_5, C_7, C_8, C_9, \) and \( C_{10} \).
The determinant of the remaining terms (C₁, C₆, and C₁₁) is

\[
\begin{vmatrix}
0 & 0 & 1 \\
3 & 1 & -3 \\
-1 & 0 & 0 \\
\end{vmatrix} = 1
\]

Since this is not equal to zero (non-singular), the resulting equations are independent and the equations are valid. Equations (3), (4), and (5) is a 3x11 matrix from which 165 combinations of 3x3 square matrices can be tested for nonsingularity. However, by inspection, the determinant mainly zeroes out (identically zero rows) except towards either end of the 3x11 matrix.

The steps which follow is an iteration process in which the Cᵢs are each sequentially assigned values equal to 1 and the remaining Cᵢs zeroed. Substitution of the numerical values of Cᵢs to (3), (4), and (5) yield the desired combination of dimensionless quantities.

Set C₂ = 1 (exponent of P) and C₃ = C₄ = C₅ = C₇ = C₈ = C₉ = C₁₀ = 0. Substitute these to (3), (4), and (5). Thus, C₆ = -1, corresponding to the exponent of C₇ from (2).

\[\pi₁ = P/C₇\]

Next, set C₃ = 1 and C₂ = C₄ = C₅ = C₇ = C₈ = C₉ = C₁₀ = 0.
Substitute these to (3), (4), and (5). From here $C_6 = -1$ or

$$\pi_2 = \frac{D_{ave}}{C_h}$$

Continue the iteration. Set $C_4 = 1$ and $C_2 = C_3 = C_5 = C_7 = C_8 = C_9 = C_{10} = 0$. Substitute these to (3), (4), and (5). Thus, $C_6 = -1$ or

$$\pi_3 = \frac{D_f}{C_h}$$

At $C_5 = 1$ and $C_2 = C_3 = C_4 = C_7 = C_8 = C_9 = C_{10} = 0$. Substitute these to (3), (4), and (5). Thus, $C_6 = -1$ or

$$\pi_4 = \frac{L_f}{C_h}$$

At $C_7 = 1$ and $C_2 = C_3 = C_4 = C_5 = C_8 = C_9 = C_{10} = 0$. Substitute these to (3), (4), and (5). Therefore, $C_6 = -1$ or

$$\pi_5 = \frac{C_o}{C_h}$$

At $C_8 = 1$ and $C_2 = C_3 = C_4 = C_7 = C_8 = C_9 = C_{10} = 0$. Substitute these to (3), (4), and (5). The results are: $C_1 = -1$ and $C_6 = 2$ or
\[ \pi_6 = \frac{NC_h^2}{Q} \]

A quick check shows that \( C_h \) needs an exponent of 3 in order for \( \pi_6 \) to be dimensionless. Thus, the proper form for it is

\[ \pi_6 = \frac{NC_h^3}{Q} \]

At \( C_9 = 1 \) and \( C_2 = C_3 = C_4 = C_5 = C_7 = C_8 = C_{10} = 0 \). Substitute these to (3), (4), and (5). This gives \( C_4 = -2 \) and \( C_6 = 5 \) or

\[ \pi_7 = C_h^5 G/ Q^2 \]

Lastly, set \( C_{10} = 1 \) and \( C_2 = C_3 = C_4 = C_5 = C_7 = C_8 = C_9 = 0 \). Substitute these to (3), (4), and (5). Thus, \( C_6 = -4 \) and \( C_{11} = -1 \) or

\[ \pi_8 = T/\rho C_h^4 \]

To summarize,

\[ \pi_1 = P/C_h \]
\[ \pi_2 = D_{ave}/C_h \]
\[ \pi_3 = D_z/C_h \]
\[ \pi_4 = L_z/C_h \]
\[
\begin{align*}
\pi_5 &= \frac{C_d}{C_h} \\
\pi_6 &= \frac{NC_h^3}{Q} \\
\pi_7 &= \frac{C_h^6 G}{Q^2} \\
\pi_8 &= \frac{T}{\rho C_h^4}
\end{align*}
\]

By inspection \(\pi_6\) and \(\pi_7\) can be combined so as to reduce the number of \(Q\)'s appearing in the \(\pi\) - terms. This gives

\[
\frac{1}{\pi_6} \pi_7 = \frac{Q^3}{NC_h^8 G}
\]

Therefore, expressions for \(Q\) and \(T\) may be written as follows:

\[
\begin{align*}
Q^3/NC_h^8 G &= \phi(P/C_h, D_{ave}/C_h, D_1/C_h, L_7/C_h, C_d/C_h, \mu) \\
T/\rho C_h^4 &= \phi'(P/C_h, D_{ave}/C_h, D_1/C_h, L_7/C_h, C_d/C_h, \mu)
\end{align*}
\]

**D.2 Diverging vane-belt sorter**

Table 2. Variables and dimensions of the vane belt sorter.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description of quantity</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>Included angle of vane belt</td>
<td>-</td>
</tr>
<tr>
<td>(L_b)</td>
<td>Length of vane belt, in.</td>
<td>L</td>
</tr>
<tr>
<td>(H)</td>
<td>Height of vane belt, in.</td>
<td>L</td>
</tr>
<tr>
<td>(C_h)</td>
<td>Clearance at hopper end, in.</td>
<td>L</td>
</tr>
</tbody>
</table>
C₀ Clearance at outlet end, in. L

Forces
V Linear velocity of belt, in/min LT⁻¹
G Acceleration due to gravity, in/sec² LT⁻²
T Torque required to operate sorter, in-lb FL
Q Volumetric capacity, in³/min

Properties of material
ρ Bulk density of material, lb/in³ FL⁻³
μ Coefficient of friction, material to belt

Setting up the general functional relationship we obtain

\[ 1 = C₀ρTGVC₀C₀HL₀μ \]

where \( C₀ \) is a constant which depends on the quantities in the function.

Denoting by \( c_i \)'s the exponents of the quantities we get

\[ 1 = Q^1ρ^{c_2}T^{c_3}G^{c_4}V^{c_5}C₀^{c_6}C₀^{c_7}H^{c_8}L₀^{c_9} \]

where \( C₀ \) is a constant which depends on the quantities in the function.

Replacing the quantities by its dimensions we have

\[ 1 = (LT⁻¹)^{c_1}(FL⁻³)^{c_2}(FL)^{c_3}(LT⁻²)^{c_4}(LT⁻¹)^{c_5}(L)^{c_6}(L)^{c_7}(L)^{c_8}(L)^{c_9} \]

Writing the auxiliary equations,
F: \[ 0 = C_2 + C_4 \]

L: \[ 0 = 3C_1 - 3C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 \]

T: \[ 0 = C_1 + 2C_4 + C_5 \]

Arbitrarily assign values to \( C_2, C_4, C_6, C_7, C_8, \) and \( C_9 \). The determinant of the remaining terms \( (C_1, C_3, \) and \( C_5) \) is

\[
\begin{vmatrix}
0 & 1 & 0 \\
3 & 1 & 1 \\
1 & 0 & 1 \\
\end{vmatrix} = -2
\]

Since this is not equal to zero the resulting equations are independent and the equations are valid.

Start an iteration process by assigning individual \( C_i \)s equal to 1 and the remaining \( C_i \)s zeroed. Substitution of the numerical values of \( C_i \)s to (3), (4), and (5) yield the desired combination of dimensionless quantities.

Set \( C_2 = 1 \) and \( C_4 = C_6 = C_7 = C_8 = C_9 = 0 \). Substitute these to (3), (4), and (5). Thus, \( C_1 = 2 \) \( C_3 = -1 \) and \( C_5 = -2 \), or

\[ \pi_1 = \frac{\rho Q^2}{TV^2} \]

At \( C_4 = 1 \) and \( C_2 = C_6 = C_7 = C_8 = C_9 = 0 \). Substitute these to (3), (4), and (5). This gives \( C_1 = 1/2 \) and \( C_5 = -5/2 \), or

\[ \pi_2 = \left(\frac{Q}{V^3}\right)^{1/2} G \]

At \( C_6 = 1 \) and \( C_2 = C_4 = C_7 = C_8 = C_9 = 0 \). Substitute these to (3), (4),
and (5). Therefore, $C_1 = -1/2$ and $C_5 = 1/2$, or

$$\pi_3 = (V/Q)^{1/2} C_0$$

Next at $C_7 = 1$ and $C_2 = C_4 = C_6 = C_8 = C_9 = 0$. Substitute these to (3), (4), and (5). Thus, $C_1 = -1/2$ and $C_5 = 1/2$, or

$$\pi_4 = (V/Q)^{1/2} C_h$$

Continue the process. Set $C_9 = 1$ and $C_2 = C_4 = C_6 = C_7 = C_8 = 0$. Substitute these to (3), (4), and (5). Hence, $C_1 = -1/2$ and $C_5 = 1/2$, or

$$\pi_5 = (V/Q)^{1/2} H$$

Lastly set $C_9 = 1$ and $C_2 = C_4 = C_6 = C_7 = C_8 = 0$. Substitute these to (3), (4), and (5). Thus, $C_1 = -1/2$ and $C_5 = 1/2$, or

$$\pi_6 = (V/Q)^{1/2} L$$

To summarize, the following are the dimensionless groups:

$$\pi_1 = \rho Q^2 / TV^2$$
$$\pi_2 = (Q/V^5)^{1/2} G$$
$$\pi_3 = (V/Q)^{1/2} C_0$$
$$\pi_4 = (V/Q)^{1/2} C_h$$
$$\pi_5 = (V/Q)^{1/2} H$$
$$\pi_6 = (V/Q)^{1/2} L$$

Inspection of the $\pi$-terms above suggests the following simplification,

$$\pi_4 / \pi_1^{1/2} = (T/\rho)^{1/4} G/V^2$$
$$\pi_3 / \pi_4 = C_h / C_h$$
$$\pi_5 / \pi_4 = H / C_h$$
\[ \pi_6 / \pi_5 = L_d / C_o \]
\[ \pi_6 / \pi_5 = L_d / H \]

Therefore, expressions for Q and T may be written as follows:

\[ Q / T V^2 = \phi(C_d / C_h, H / C_h, L_d / C_o, L_d / H, \mu, \alpha) \]
\[ (T / p) G / V^2 = \phi(C_d / C_h, H / C_h, L_d / C_o, L_d / H, \mu, \alpha) \]

**E. Prediction of particle position, velocity and acceleration in a cylindrical roller sorter**

A point in space \( q(x, y, z) \) traveling along a screw path (translation and rotation) may be described by matrices. Initially, we define points \( p_1 \) and \( p \) along the axis \( u \) through which pure translation occurs over a distance \( s \) and points \( q_t \) and \( q \) which undergo rotation through angle \( \phi \). This is shown in the figure below:

![Figure 1. The screw coordinate system](image)
In matrix form screw motion in space can be represented by

\[ [q - p] = [R_{\phi,u}] (q_1 - p_1) \]

where

\[ p = p_1 + su \]

\[ R_{\phi,u} = \text{spatial rotation matrix.} \]

Expanding (1) in 4\times4 matrix we have

\[
\begin{vmatrix}
q_x \\
q_y \\
q_z \\
1
\end{vmatrix} = \begin{vmatrix}
[R_{\phi,u}] & (p_1 + su - [R_{\phi,u}]p_1) \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1
\end{vmatrix}
\]

(1a)

The 4\times4 rotation matrix \([R_{\phi,u}]\) has the following elements (obtained by successive multiplication of rotation matrices with respect to x,y,z, and u axes):

\[
[R_{\phi,u}] = \begin{vmatrix}
(u_x^2V\phi + C\phi) & (u_xu_yV\phi - u_zS\phi) & (u_xu_zV\phi + u_yS\phi) \\
(u_xu_yV\phi + u_zS\phi) & (u_y^2V\phi + C\phi) & (u_yu_zV\phi - u_xS\phi) \\
(u_xu_zV\phi - u_yS\phi) & (u_yu_zV\phi + u_xS\phi) & (u_z^2V\phi + C\phi)
\end{vmatrix}
\]

(1b)
Where

\[ V\phi = \text{vers}\phi = 1 - \cos\phi \quad (1c) \]

\[ S\phi = \sin\phi \]

\[ C\phi = \cos\phi \]

To find an expression for \([R_{\phi,u}]\) if \(u\) is coincident with the z-axis as in Figure 1 we have

\[ u_x = u_y = 0 \text{ and } u_z = 1 \text{ since } \]

\[ |u| = 1 \text{ (or } u_x^2 + u_y^2 + u_z^2 = 1). \]

Thus, \([R_{\phi,u}]\) can be simplified and is equal to

\[
[R_{\phi,u}] = \begin{bmatrix}
\cos\phi & -\sin\phi & 0 \\
\sin\phi & \cos\phi & 0 \\
0 & 0 & 1\end{bmatrix}
\]

(1d)

Re-writing (1a) in terms of (1d) and taking the origin as reference point \(p_1\) \((p_{1x}, p_{1y}, p_{1z})\) we have the following matrix:

\[
\begin{bmatrix}
q_x \\
q_y \\
q_z \\
1
\end{bmatrix} = \begin{bmatrix}
\cos\phi & -\sin\phi & 0 \\
\sin\phi & \cos\phi & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
(q_{1x} + su_x - p_{1x}\cos\phi + p_{1y}\sin\phi - p_{1z}(0)) \\
(q_{1y} + su_y - p_{1x}\sin\phi - p_{1y}\cos\phi - p_{1z}(0)) \\
(p_{1z} + su_z - p_{1z}(0) - p_{1y}(0) - p_{1z}(1)) \\
1
\end{bmatrix}
\]

(1e)

At the origin \(p_{1x} = p_{1y} = p_{1z} = 0\). Therefore, (1e) can now be written as
To find the coordinates of point \( q \) if translational distance covered is \( 1, \phi = 45^\circ \), and \((q_{lx}, q_{ly}, q_{lz}) = (0, 3.0125, 0)\). Here, the actual radius of the cylindrical roller is used (3.0125 in.).

From (3)

\[
q_x = (\cos45^\circ)(0) - (\sin45^\circ)(3.0125) = 0 - 2.13 = -2.13
\]

\[
q_y = (0)(\sin45^\circ) + (3.0125)(\cos45^\circ) = 0 + 2.13 = 2.13
\]

\[
q_z = 0 + 1
\]

\((q_x, q_y, q_z) = (-2.13, 2.13, 1)\)

Differential rotation matrices:

Expressions for the angular velocity and acceleration of a point in a screw will be developed as follows

\[
v = [R]v_1 \quad (2)
\]

or,

\[
v_1 = [R]^{-1}v = [R]^Tv \quad (2a)
\]

Taking a time derivative (primes denote derivatives),

\[
v' = [R']v_1 + [R]v_1' \quad (3)
\]

\[
v_1' = 0 \text{ (reference point)}
\]

\[
v' = [R']v_1 \quad (3a)
\]
Thus, the angular velocity matrix \([W]\) is obtained by getting the product of the first derivative of the rotation matrix and its transpose.

Also,

\[ v' = \Phi' \times v \]  

where \(\Phi' = \phi' u\) and \(v' = \frac{dv}{dt}\) as before.

Thus,

\[ v'' = \Phi'' \times v + \Phi' \times v \]  

Substitute (5) in (6)

\[ v'' = \Phi'' \times v + \Phi' \times (\phi' \times v) \]  

where \(\Phi'' = \phi'' u + \phi' u'\)

and substitute (6a) in (6b)

\[ v'' = (\phi'' u + \phi' u') \times v + \phi' u \times (\phi' \times v) \]

\[ = (\phi'' u + \phi' u') \times v + \phi^2 [u \times (u \times v)] \]  

In matrix form it is,

\[ v'' = [\phi'' [P_u] + \phi' [P'_u] + \phi^2 [P_u][P_u]] v \]

\[ v'' = [W'] v. \]

where

\[ [P_u] = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix} \]
The angular acceleration matrix is denoted by shorthand form \([W']\).

This is expanded into the following

\[
[W'] = \begin{bmatrix}
(u_x^2-1)\phi^2 & (u_xu_y\phi^2-u_z\phi'\phi''-u_z\phi') & (u_xu_y\phi^2+u_y\phi'+u_y\phi'') \\
(u_xu_y\phi^2+u_y\phi'+u_y\phi'') & (u_y^2-1)\phi^2 & (u_yu_z\phi^2-u_z\phi'\phi''-u_z\phi') \\
(u_yu_z\phi^2-u_z\phi'\phi''-u_z\phi') & (u_yu_z\phi^2-u_z\phi'+u_z\phi'') & (u_z^2-1)\phi^2
\end{bmatrix}
\]

To find the angular velocity and acceleration of the screw in Figure 1, it is needed to first calculate \([R_v,u'] [R_v,u]^T\) using (4) as follows
This results in

\[
\begin{pmatrix}
\phi^2 & 0 & 0 & 0 \\
0 & \phi^2 & 0 & 0 \\
0 & 0 & s^2 u_z^2 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

Since \( u^2 = 1 \) the preceding angular velocity matrix reduces to

\[
\begin{pmatrix}
\phi^2 & 0 & 0 & 0 \\
0 & \phi^2 & 0 & 0 \\
0 & 0 & s^2 & 0 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

The angular acceleration is obtained by using the following expressions for \([P_u]\) and \([Q_u]\):

Substituting \( u_z = u_y = 0 \) and \( u_z = 1 \),

\[
[P_u] = \begin{pmatrix}
0 & -1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}, \quad [Q_u] = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
Therefore, applying (8), the angular acceleration matrix is

\[
\begin{bmatrix}
-\phi'' & 0 & 0 \\
0 & -\phi'^2 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

where \( u_z' = 0 \) since \( u \) is along z-axis

To find an expression for linear velocity and acceleration we differentiate (1) as follows

\[
q' = [W] (p_1' + s' u + s u' - [W]p_1) q
\]

\[
\begin{bmatrix}
0 \\
0 \\
1 \\
1
\end{bmatrix}
\]
where \( \mathbf{p}_1 = \mathbf{p}_0 \) reference point, constant, thus \( \mathbf{p}_1' = 0 \) and \( s'u' = 0 \) since \( s' \) is along instantaneous screw direction.

Thus,

\[
\begin{vmatrix}
\mathbf{q}'
\end{vmatrix} = \begin{bmatrix} W & (s'u-[W]\mathbf{p}_0) \\ 0 & 0 & 1 & 1 \end{bmatrix} \mathbf{q} \tag{10a}
\]

\[
= \begin{bmatrix} V \end{bmatrix} \mathbf{q} \tag{10b}
\]

Writing the elements of \([V]\)

\[
\begin{bmatrix} V \\ v \end{bmatrix} = \begin{bmatrix} 0 & -u_z \phi' & u_y \phi' & (s'u_x - u_z \phi' p_{ox} - u_y \phi' p_{oz}) \\ u_z \phi' & 0 & -u_y \phi' & (s'u_y - u_z \phi' p_{ox} - u_x \phi' p_{oz}) \\ -u_y \phi' & u_x \phi' & 0 & (s'u_z - u_y \phi' p_{ox} - u_x \phi' p_{oy}) \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{10c}
\]

To get the linear acceleration we differentiate (10) and obtain

\[
\begin{vmatrix}
\mathbf{q}''
\end{vmatrix} = \begin{bmatrix} W' & (s'' + s'u' - [W']\mathbf{p}_0 - [W]\mathbf{p}_0' \\ 0 & 0 & 1 \end{bmatrix} \mathbf{q} \tag{11}
\]

Or,
\[
\begin{bmatrix}
q'' \\
0
\end{bmatrix} = [A] \begin{bmatrix} q \\ 1 \end{bmatrix} \tag{11a}
\]

The acceleration matrix, \([A]\) contains the following elements:

\[
\begin{bmatrix}
d_{11}'' & d_{12}'' & d_{13}'' & (s'u_x + s'u_x' + u_z'p_{o_y} - u_y'p_{o_x} - d_{11}'')p_{o_x} - d_{12}'')p_{o_y} - d_{13}'')p_{o_z} \\
d_{21}'' & d_{22}'' & d_{23}'' & (s'u_y + s'u_y' + u_x'p_{o_x} + u_y'p_{o_z} - d_{21}'')p_{o_x} - d_{22}'')p_{o_y} - d_{23}'')p_{o_z} \\
d_{31}'' & d_{32}'' & d_{33}'' & (s'u_z + s'u_z' + u_y'p_{o_y} - u_y'p_{o_y} - d_{31}'')p_{o_x} - d_{32}'')p_{o_y} - d_{33}'')p_{o_z} \\
0 & 0 & 0 & 0
\end{bmatrix}
\tag{11b}
\]

where

\[
\begin{align*}
d_{11}'' &= (u_x^2 - 1)\phi'^2 \\
d_{12}'' &= (u_xu_y\phi'^2 - u_x'\phi'' - u_y\phi'') \\
d_{13}'' &= (u_xu_z\phi'^2 + u_y'\phi'' + u_y\phi'') \\
d_{21}'' &= (u_yu_y\phi'^2 + u_y'\phi'' + u_y\phi'') \\
d_{22}'' &= (u_y^2 - 1)\phi'^2 \\
d_{23}'' &= (u_yu_z\phi'^2 - u_x'\phi'' - u_x\phi'') \\
d_{31}'' &= (u_xu_z\phi'^2 - u_y'\phi'' - u_y\phi'') \\
d_{32}'' &= (u_yu_z\phi'^2 - u_x'\phi'' - u_x\phi'') \\
d_{33}'' &= (u_z^2 - 1)\phi'^2
\end{align*}
\]

Also,

\[
\begin{align*}
p_{o_x}'' &= s'u_x + s'u_x' + u_z'p_{o_y} - u_y'p_{o_x}' \\
p_{o_y}'' &= s'u_y + s'u_y' - u_x'p_{o_x} + u_y'p_{o_z}'
\end{align*}
\]
\[ p_{oy}'' = s'u_x + s'u_y + u_x \phi' p_{ox}' - u_y \phi' p_{oy}' \]

Where \( p_0' = (p_{ox}', p_{oy}', p_{oz}') = (s'u_x, s'u_y, s'u_z) \)

To develop expressions for linear velocity and acceleration for the screw in figure 1 refer to (10c) where

\[
[v] = \begin{bmatrix}
0 & -u_z \phi' & 0 & (-u_z \phi' p_{oy}) \\
 u_z \phi' & 0 & 0 & (-u_z \phi' p_{ox}) \\
0 & 0 & 0 & (s'u_z) \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

Or, substituting the appropriate values,

\[
[v] = \begin{bmatrix}
0 & -\phi' & 0 & 0 \\
\phi' & 0 & 0 & 0 \\
0 & 0 & 0 & s' \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

Using (11b)
\[
\begin{pmatrix}
-\phi'^2 & -(u_z\phi' + u_z\phi'') & 0 & 0 & (u_z\phi'p_{oy}' + \phi'^2p_{ox} + (u_z\phi' + u_z\phi'')p_{oy}) \\
(u_z\phi' + u_z\phi'') & -\phi'^2 & 0 & 0 & (-u_z\phi'p_{ox}' - (u_z\phi' + u_z\phi'')p_{ox} + \phi'^2p_{oy}) \\
0 & 0 & 0 & 0 & (s''u_z + s'u_z) \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

This is equal to

\[
\begin{pmatrix}
-\phi'^2 + \phi'' & 0 & 0 & 0 \\
\phi'' & -\phi'^2 & 0 & 0 \\
0 & 0 & 0 & (s'' + s') \\
0 & 0 & 0 & 0
\end{pmatrix}
\]

From Figure 1,

\[p_{ox}'' = u_z\phi'p_{oy}' = \phi'p_{oy}'\]

\[p_{oy}'' = -u_z\phi'p_{ox}' = -\phi'p_{ox}'\]

\[p_{ox}'' = s''u_z + s'u_z' = s''\]
VITA

The author was born on August 4, 1949 in Odiongan, Romblon, Philippines. His parents are Artemio I. Tagonan (deceased) and Antonia A. Gaac both schoolteachers who worked in the government’s public school system prior to retirement.

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The author is happily married to Evangeline A. Arguelles who teaches mathematics at the University of Southern Mindanao. They have two wonderful kids: Andrew, 18 and Emily, 14.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Rommel G. Tangonan

Major Field: Engineering Science


Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Date of Examination:

October 30, 1995